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Experimentation on Nebraska Farms for Sustaining Soil Health Management

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EXPERIMENTATION ON NEBRASKA FARMS FOR SUSTAINING SOIL HEALTH MANAGEMENT

by

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A DISSERTATION

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EXPERIMENTATION ON NEBRASKA FARMS FOR SUSTAINING SOIL HEALTH MANAGEMENT

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Soil health management practices have increasingly been promoted across US agroecosystems to address many interrelated environmental and economic food system challenges. Sustaining conservation behavior – through farmer's adoption and continued use of practices – is key for achieving many soil health-related intended social-ecological benefits. Using a range of scientific methods, from lab-based experiments to on-farm research to farmer interviews, the overall objective of this dissertation research was to explore soil and human dimension considerations to design farming and knowledge transfer systems for sustaining soil health management in the US Midwest. In a multivariate analysis of ten on-farm research sites, we found that ecological intensification of cropping systems via cover crop use had the greatest impact on changes in properties related to soil organic matter (SOM), carbon (C) and nitrogen (N) dynamics. The study also highlighted the potential of synthetic fertilizer reductions and economic savings from improved soil biological activity via longer cover crop use. Analyses comparing four on-farm sites with annual crop rotations with and without cover crops (i.e., cropland soils) with perennial grassland sites (i.e., reference soil) found that framing soil metrics relative to reference soils and ensuring appropriate sampling intensity were important to quantify cover crop impacts on farms. Analysis of C and N distribution at the same four sites using SOM fractions of distinct ecological relevance found less pronounced cover crop effects but highlighted the potential of perenniality as an approach to agroecosystem design for improved SOM C and N dynamics and related soil functions. Through analysis of in-depth interviews, interactive activities, and annual on-farm reports, we identified five distinct factors supporting farmer's social networks influences on sustained use of soil health practices: land tenure, perceived acceptance, family farming traditions, co-learning, as well as on-farm experimentation and adaptive management. By linking learnings from on-farm experimentation and factors related to farmers' social and informational networks, this research advances important lessons for conservation efforts with respect to soil health assessment, sampling approach, and knowledge transfer.

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An overflow of joy surrounds me as I reflect on the last four years of this journey of growth, both personally and professionally. As the saying goes “If you want to go fast, go alone. If you want to go far, go together.” The completion of this dissertation would not have been possible without the support and nurturing of many along the way.

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PREFACE

CHAPTER 2 has been published in *Geoderma*

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CHAPTER 4 is currently under preparation for submission to Soil Use and Management Journal

Krupek, F. S., Kaiser, M., Redfearn, D., & Basche, A. "*Carbon and nitrogen content in cover crop on-farm experiments using soil organic matter fractions and reference sites*"

CHAPTER 5 is currently under preparation for submission to Renewable Agriculture and Food Systems Journal

Krupek, F. S., Ruth, T., Redfearn, D., & Basche, A. "*Exploring the influence of social networks to sustain soil health management*"

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 : GENERAL INTRODUCTION

"When we see land as a community to which we belong, we may begin to use it with love and respect."
-Aldo Leopold**,** *A Sand County Almanac*.

Agriculture in Midwest USA

Despite increased enthusiasm around sustainable agriculture over the past decades, many enterprises in the Midwest US have shown to still lack resilience by being vulnerable to extreme weather events and market fluctuations (Prokopy et al., 2020; Hart et al., 2020; NOAA, 2020a, 2020b; Westhoff et al., 2020). The pursuit of higher cropland productivity during the Green Revolution of the mid-20th century has been accompanied by mounting environmental and social trade-offs nowadays. For example, management practices have led to soil degradation through processes such as erosion and soil organic matter (SOM) depletion (Lal, 2020; Prokopy et al., 2020). Additionally, many urban and rural communities in the Midwest USA face social challenges such as malnutrition and poverty (Smith et al., 2010). Soil health is at the forefront of several agricultural sustainability discussions as an opportunity to "connect the dots" between proper soil management and broader economic, environmental, and societal outcomes. Thus, soil health has been elevated in recent years as an approach to address many interrelated environmental and economic food system concerns, with increasing momentum for directing agricultural research and policy agendas.

Soil health

Soil health is commonly defined as "continued capacity of soils to function as a vital living ecosystems that sustains plants, animals, and humans" (USDA-NRCS, 2018). Agricultural management considerations such as reduced tillage (i.e., where farmers avoid plowing soils), cover crops (i.e., plants grown to cover the soil after the main crop is harvested), resource-conserving and diverse crop rotation (i.e., add small grains, cool-season, and pulse crops in the rotation over several years), and crop-livestock integration are known to reduce soil disturbance, shorten periods of bare soil in fall, winter, and spring, as well as maximize crop diversity (USDA–NRCS, 2018) while meeting several soil health goals (Basche & DeLonge, 2019; Taylor et al., 2016; MacLaren et al., 2019). The emerging interest in these practices across the United States aims to incorporate practices that can help meet both agricultural sustainability and production goals (Delgado et al., 2011). Despite increased enthusiasm and awareness of the importance of proper soil management, adoption of soil health-promoting practices represents less than 14% of the current U.S. land capacity (USDA-NASS, 2019).

Collaborative research and farmer-led initiatives supporting soil health

Intensified conservations about management practices to ensure the best use of soil resources have fostered policy tools and initiatives to promote soil health research and practices adoption on farmlands. For example, the US Department of Agriculture (USDA) is a leading funder of programs that incentivize pro-environmental agricultural practices: the Conservation Reserve Program (CRP), the Environmental Quality Incentives Program (EQIP), and the Conservation Stewardship Program (CSP) are examples of programs administered by the agency (Czap et al., 2019). Many state agencies across the US are also exploring approaches to support additional soil health research and outreach efforts. For example, the recently introduced Massachusetts Healthy Soils Bill proposes the establishment of a Soil Health Program to provide farmers with financial, technical, and educational incentives to increase cropping system productivity and resiliency (An act to promote healthy soils, 2018). Aiming to link soil health and water conservation practices, the New Mexico Healthy Soil Act aims to establish a statewide network for managing lands for soil health (The health soil act, 2019). The Soil Health and Recovery Monitoring System, proposed by an Iowa bill, aims to pave the way to help researchers and farmers advocating for agricultural conservation practices (An Act providing for a statewide soil resource health and recovery monitoring system, 2019). Also, recognizing the benefits of soil health-building practices, Nebraska legislators have passed or introduced bills, such as the Soil Health Task Force and the Soil Health & Productivity Incentive Act, aiming to establish and implement practices that improve soil health (Create the Healthy Soils Task Force, 2019). These state soil health initiatives and legislative efforts across the US demonstrate the increased interest in innovative policies to develop a network of synergistic partnerships to enhance research and adoption of soil health-promoting practices (Soil for climate, 2019).

Nebraska-NRCS Soil Health Initiative

The Nebraska USDA-NRCS Soil Health Initiative (SHI) is an example of a voluntary incentive program aimed at demonstrating the use of a soil health management systems by planting cover crops, changing crop rotation, and implementing any other conservation practice supporting soil health. The initiative is a cross-sector collaboration between the University of Nebraska (UNL) On-Farm Research Network, the Natural Resources Conservation Service, and Nebraska landowners. Through the SHI, farmers established a 5-year demonstration project with in-field management comparisons across the state to showcase cover crop management and cropping system comparisons.

All farmers approved under this initiative conducted strip trials including cover crops in some capacity, some included different species comparisons, and others grazing or crop rotation in field-wide treatments. Project funding came primarily through EQIP to fund outreach, education, meetings, field days, soil health assessment equipment, and implementation of demonstration plots in producer's land. Many partners, including extension educators, faculties, and graduate students from the University of Nebraska-Lincoln, soil scientists and staff members from NRCS, and local farmers and agricultural retailers, came together to work on this project, each bringing their own strengths to the endeavor. Due to the project participation (agency and citizen) and because farmers with cost-share funding must work within the regulatory framework of Farm Bill programs, the project can be classified as a mixed partnership (Moore & Koontz, 2003) or largely community-driven agency/citizen partnership (Church & Prokopy, 2017).

The project began in 2017 and was completed in 2021. In total, 17 farmers were under contract through Farm Bill programs representing 1793 acres of on-farm trial. Producer total acres farmed or managed ranged from 400 to 5,000. The on-farm trials rationale, objectives, results, and observations were compiled yearly into annual reports, the On-Farm Research Results, along with other on-farm studies within the University of Nebraska-Lincoln Extension. Data from these reports were disseminated in field days and annual meetings hosted by the On-Farm Research Network to share the research findings (Thompson et al., 2019). This gathering brought together farmers, agronomists, industry, government employees, and university faculty and students and provides participating farmers with the opportunity to present their research projects and speak about their experiences and knowledge gained.

Gaps in soil health-related research and outreach programming

Management practices that meet several soil health goals are increasingly an emphasis of the agricultural research and policy agenda. To advance sustaining soil health management systems, it is important that research efforts are translational and genuinely supportive of practitioner-collaborator, on-the-ground local improvements. The following gaps in both research (i.e., experimental data) and extension (i.e., science-based engagement) represent opportunities for embracing soil health as an overarching principle aligned with sustainability goals.

Emerging soil health assessments with greater inclusion of physical and biological indicators

Soil health assessments include a suite of biological, chemical, and physical properties that are used to infer about soil functions such as water infiltration, carbon sequestration, nutrient retention, erosion control, and below-ground biodiversity. To be used as soil health indicator, soil properties should be 1) relevant to soil health, ecosystem function, and services, 2) sensitive to management changes, and 3) practical. The latter mean analyzed at low cost and in a timely fashion (Lehmann et al., 2020). Historically, soil health assessments focused on crop production and were usually soil fertility oriented. Over the years, studies have gradually incorporated soil health to also include the role of soils in water quality (Lehmann et al., 2020) and climate change (Allen et al., 2011). However, soil health assessments are still dominated by chemical properties, which make up from 40% to 90% of the indicators in soil health assessment frameworks. Therefore, there is a need for better understanding of biological indicators of farm-available soil health assessments, which currently constitutes fewer than 20% of the indicators (Lehmann et al., 2020). Additionally, a better understanding of the causality between biological indicators and farm outcomes (e.g., profitability, resource use efficiency, and drought resilience) is critically needed in the next frontier in soil-health research.

Realistic or attainable gains in soil health with management changes

A gap in the literature also exists concerning soil health metrics and assessments in terms of condition relative to soil capacity defined through a reference state or condition. Reference state reflects zones that have been less affected by human activities; either native virgin land or undisturbed soils, with a minimum degree of anthropogenic modification of soil properties due to management or land-use change. There are some early-stage, exploratory research efforts to map soil classes that can be used as a reference state (Dobarco et al., 2021). Framing soil health metrics relative to a reference state is critical for guiding farmers and stakeholders in the decision-making process and assisting in forecasting realistically attainable improvements in soil properties with management decisions (Tugel et al., 2005).

The role of soil sampling approaches on quantifying management success on farms

Over the last decade, much soil health-related scientific progress has been made, particularly on the verification of soil health methods and metrics by land-grant universities (e.g., Cornell Soil Health Assessment Framework by Cornell University) and non-profit organizations (e.g., Tier 1 and 2 Soil Health Indicators by the Soil Health Institute). However, soil sampling standardization, particularly in terms of soil depth and number of replications, is still missing from soil health studies and would substantially improve our ability to compare and contrast results from different studies (Stewart et al., 2018).

Soil nutrient cycling using emergent views of the nature of soil organic matter

There is also a need for improved quantitative and process-level understanding of the impact of soil health practices on soil organic matter dynamics and pools of unprotected and mineral-protected soil organic matter in agricultural soils. More recently, government and private-led proposals have encouraged carbon sequestration through financial incentives and carbon farming programs (Fleming et al., 2019; Wolf and Ghosh, 2020). These have spurred further adoption of so-called climate-smart management practices and revitalized the conversation around agricultural systems' carbon footprint. Still under discussion are the most efficient ways to measure, report and verify SOM changes influenced by land use and soil management for inferences on soil carbon sequestration and atmospheric greenhouse gas removal (Smith et al., 2020).

Human dimensions of agricultural decision-making

Farmers' behavioral persistence towards soil health practices beyond the spatial and temporal scope of on-farm research and incentive programs is highly important to achieve long-term sustainability goals. Many changes in physical, chemical, and biological soil properties, as well as agronomic responses that indicate improvements in soil health, are complex and variable. For example, soil aggregate stability, infiltration rates, and microbial indicators quantified by meta-analysis are shown to be very responsive (1-3 years for changes detection) to changes in cover crop and no-tillage adoption (Steward et al., 2018). However, other soil properties, such as organic carbon accumulation, might take over five years to detect significant changes due to management interventions that reverse soil degradation (Angers & Eriksen-Hamel, 2008). Because of the complexity of agricultural systems and management choices affecting soil degradation, research expanding beyond the laboratory and field settings are required. Including social science research within agricultural conservation programs can help in successfully designing conservation strategies, selecting producer's behavioral targets, and evaluating results by measuring conservation behavior (Akerlof & Kennedy, 2013). To fully understand farmers' adoption and continued use of soil health practices and engagement in soil conservation communication, it is important to explore the social mechanisms and human dimensions underlying farmers' communication networks and information processing on soil health.

Dissertation organization

Considering the identified gaps, the overall objective of this applied research integrated with extension was to advance understanding of how soil and human dimension considerations impact farming and knowledge transfer systems for sustaining soil health management Nebraska.

Chapter two investigated the effect of soil management on physical, chemical and biological properties from field-scale soil health assessment. We developed a framework that classified spatial and temporal ecological intensification with soil health practices (i.e., tillage, crop rotation, cover crop, organic amendment, and crop-livestock integration) from ten collaboratively designed on-farm sites. My research questions for this project were: What is the relationship between ecological intensification and soil properties? How does ecological intensification influence physical, chemical, and biological soil properties? What is the relationship between nutrient recommendation and savings and ecological intensification?

Chapter three is an analysis of data collected from four on-farm sites representing a cropland-grassland gradient. We compared cropland soils with annual row crop rotations with and without cover crops to perennial grassland reference soils. We developed a framework that quantified soil health relative to a reference soil by examining physical, chemical, and biological properties in near-surface soil. My research questions for this project were: What are the realistic or attainable gains in soil health with cover crops? How do gains in soil health relate to grain yield? What are the sampling strategies that maximally distinguish soils with a perenniality gradient (i.e., from reference to cropland sites with and without cover crop)?

Chapter four used a sequential fractionation procedure that separated bulk soil organic matter (SOM) into distinct sub-compartments (e.g., particulate organic matter, water-extractable organic matter, mineral-associated organic matter) using samples from the same cropland and grassland sites described in chapter three. My research questions for this project were: How do C and N distribution within SOM fractions of distinct ecological relevance respond to soil management representing a cropland-grassland gradient? How do operationally defined fractions affect soil physicochemical and biological properties?

Chapter five investigated farmer's network and social interactions, and soil health-related beliefs, attitudes and behavioral changes. In-depth interviews, interactive activities, and annual on-farm reports were applied to participants of the Soil Health Initiative. My research questions for this project were: How do social and informational networks influence farmers' sustaining use of soil health practices? What was learned from soil and agronomic responses indicating improvements in soil health documented as part of a five-year on-farm experimentation project?

References

Akerlof, K., & Kennedy, C. (2013). Nudging toward a healthy environment: How behavioral change research can inform conservation. *White paper for the Gordon and Betty Moore Foundation*. George Mason University, Fairfax, VA.

Allen, D. E., Singh, B. P., & Dalal, R. C. (2011). Soil health indicators under climate change: a review of current knowledge. *Soil health and climate change*, 25-45. https://doi.org/10.1007/978-3-642-20256-8_2

An act promote healthy soils, H.3713, 192nd General Court of Massachusetts. (2018). https://malegislature.gov/Bills/190/HD3966 (accessed 28 March 2023).

An Act providing for a statewide soil resource health and recovery monitoring system, HF.102, The Iowa Legislature. (2019). https://www.legis.iowa.gov/publications/search/document?fq=id:1035068&q=hf102 (accessed 28 March 2023).

Angers, D. A., & Eriksen-Hamel, N. S. (2008). Full-inversion tillage and organic carbon distribution in soil profiles: A meta-analysis. *Soil Science Society of America Journal*, *72*(5), 1370-1374. https://doi.org/10.2136/sssaj2007.0342

Basche, A. D., & DeLonge, M. S. (2019). Comparing infiltration rates in soils managed with conventional and alternative farming methods: A meta-analysis. *PLoS One*, *14*(9), e0215702. https://doi.org/10.1371/journal.pone.0215702

Church, S. P., & Prokopy, L. S. (2017). The influence of social criteria in mobilizing watershed conservation efforts: A case study of a successful watershed in the Midwestern US. *Land Use Policy*, *61*, 353-367. https://doi.org/10.1016/j.landusepol.2016.11.030

Create the Healthy Soils Task Force and add a use for a fund, LB243, Legislature of Nebraska 160th legislature. (2019). https://nebraskalegislature.gov/FloorDocs/106/PDF/Intro/LB243.pdf (accessed 28 March 2023).

Czap, N. V., Czap, H. J., Banerjee, S., & Burbach, M. E. (2019). Encouraging farmers' participation in the Conservation Stewardship Program: A field experiment. *Ecological Economics*, *161*, 130-143. https://doi.org/10.1016/j.ecolecon.2019.03.010

Dayer, A. A., Lutter, S. H., Sesser, K. A., Hickey, C. M., & Gardali, T. (2018). Private landowner conservation behavior following participation in voluntary incentive programs:

Recommendations to facilitate behavioral persistence. *Conservation Letters*, *11*(2), e12394. https://doi.org/10.1111/conl.12394

Delgado, J. A., Groffman, P. M., Nearing, M. A., Goddard, T., Reicosky, D., Lal, R., ... & Salon, P. (2011). Conservation practices to mitigate and adapt to climate change. *Journal of soil and water conservation*, *66*(4), 118A-129A. https://doi.org/10.2489/jswc.66.4.118A

Dobarco, M. R., McBratney, A., Minasny, B., & Malone, B. (2021). A framework to assess changes in soil condition and capability over large areas. *Soil Security*, *4*, 100011. https://doi.org/10.1016/j.soisec.2021.100011

Fleming, A., Stitzlein, C., Jakku, E., & Fielke, S. (2019). Missed opportunity? Framing actions around co-benefits for carbon mitigation in Australian agriculture. *Land Use Policy*, *85*, 230-238. https://doi.org/10.1016/j.landusepol.2019.03.050

Hart, C.E., Hayes, D. J., Jacobs, K. L., Schulz, L. L., Crespi, J. M., 2020. The Impact of COVID-19 on Iowa's Corn, Soybean, Ethanol, Pork, and Beef Sectors. Center for Agricultural and Rural Development, Iowa State University. CARD Policy Brief 20-PB 28. https://www.card.iastate.edu/products/publications/pdf/20pb28.pdf (accessed 2 March 2022).

Lal, R. (2020). Soil organic matter and water retention. *Agronomy Journal*, *112*(5), 3265-3277. https://doi.org/10.1002/agj2.20282

Lehmann, J., Bossio, D. A., Kögel-Knabner, I., & Rillig, M. C. (2020). The concept and future prospects of soil health. *Nature Reviews Earth & Environment*, *1*(10), 544-553. https://doi.org/10.1038/s43017-020-0080-8

MacLaren, C., Storkey, J., Strauss, J., Swanepoel, P., & Dehnen-Schmutz, K. (2019). Livestock in diverse cropping systems improve weed management and sustain yields whilst reducing inputs. *Journal of Applied Ecology*, *56*(1), 144-156. https://doi.org/10.1111/jpe.2019.56.issue-110.1111/1365-2664.13239

Moore, E. A., & Koontz, T. M. (2003). Research note a typology of collaborative watershed groups: Citizen-based, agency-based, and mixed partnerships. *Society &Natural Resources*, *16*(5), 451-460. https://doi.org/10.1080/08941920309182

NOAA National Centers for Environmental Information (NCEI), 2020a. State of the Climate: National Climate Report for 2019. https://www.ncdc.noaa.gov/sotc/national/201913/supplemental/page-1 (accessed 26 January 2020).

NOAA National Centers for Environmental Information (NCEI), 2020b. U.S. Billion- Dollar Weather and Climate Disasters. https://www.ncdc.noaa.gov/billions/ (accessed 26 January 2020).

Prokopy, L.S., Gramig, B.M., Bower, A., Church, S.P., Ellison, B., Gassman, P.W., et al., 2020. The urgency of transforming the Midwestern US landscape into more than corn and soybean. Agric. Hum. Value 37 (3), 537–539. https://doi.org/10.1007/ s10460-020-10077-x.

Rakkar, M. K., & Blanco-Canqui, H. (2018). Grazing of crop residues: Impacts on soils and crop production. *Agriculture, Ecosystems & Environment*, *258*, 71-90. https://doi.org/10.1016/j.agee.2017.11.018

Ranjan, P., Duriancik, L. F., Moriasi, D. N., Carlson, D., Anderson, K., & Prokopy, L. S. (2020). Understanding the use of decision support tools by conservation professionals and their education and training needs: An application of the Reasoned Action Approach. *Journal of Soil and Water Conservation*, *75*(3), 387-399. https://doi.org/10.2489/jswc.75.3.387

Smith, C., Butterfass, J., & Richards, R. (2010). Environment influences food access and resulting shopping and dietary behaviors among homeless Minnesotans living in food deserts. *Agriculture and Human Values*, *27*(2), 141-161. https://doi.org/10.1007/s10460-009-9191-z

Smith, P., Soussana, J. F., Angers, D., Schipper, L., Chenu, C., Rasse, D. P., ... & Klumpp, K. (2020). How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Global Change Biology*, *26*(1), 219-241. https://doi.org/10.1111/gcb.14815

Soil for climate (2019). Healthy soils legislation update. https://www.soil4climate.org/news/healthy-soils-legislation-update-may-2019 (accessed 28 March 2023).

Stewart, R. D., Jian, J., Gyawali, A. J., Thomason, W. E., Badgley, B. D., Reiter, M. S., & Strickland, M. S. (2018). What we talk about when we talk about soil health. *Agricultural & Environmental Letters*, *3*(1), 180033. https://doi.org/10.2134/ael2018.06.0033

Taylor, S. D., He, Y., & Hiscock, K. M. (2016). Modelling the impacts of agricultural management practices on river water quality in Eastern England. *Journal of Environmental Management*, *180*, 147-163. https://doi.org/10.1016/j.jenvman.2016.05.002

The health soil act, HB. 204, 24th Legislature State of New Mexico. (2019). https://www.nmlegis.gov/Sessions/19%20Regular/bills/house/HB0204.pdf (accessed 28 March 2023).

Thompson, L. J., Glewen, K. L., Elmore, R. W., Rees, J., Pokal, S., & Hitt, B. D. (2019). Farmers as researchers: in-depth interviews to discern participant motivation and impact. *Agronomy Journal*, *111*(6), 2670-2680. https://doi.org/10.2134/agronj2018.09.0626

Tugel, A. J., Herrick, J. E., Brown, J. R., Mausbach, M. J., Puckett, W., & Hipple, K. (2005). Soil change, soil survey, and natural resources decision making: a blueprint for action. *Soil Science Society of America Journal*, *69*(3), 738-747. https://doi.org/10.2136/sssaj2004.0163

USDA-NASS, 2019. 2017 Census of Agriculture, Summary and State Data. U.S. Department of Agriculture National Agricultural Statistics Service. https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf (accessed 16 March 2022).

USDA–NRCS (2018). Soil health. U.S. Department of Agriculture Natural Resources Conservation Service. https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/ (accessed 28 March 2023).

Westhoff, P., Meyer, S., Binfield, J., Gerlt, S., 2020. Early Estimates of the Impacts of COVID-19 on U.S. Agricultural Commodity Markets, Farm Income and Government Outlays. Food and Agricultural Policy Research Institute, University of Missouri. FAPRI-MU Report #02–20. https://www.agri-pulse.com/ext/resources/pdfs/FAPRI-Report-02-20.pdf (accessed 2 March 2023).

Wolf, S. A., & Ghosh, R. (2020). A practice-centered analysis of environmental accounting standards: integrating agriculture into carbon governance. *Land use policy*, *96*, 103552. https://doi.org/10.1016/j.landusepol.2018.08.003

CHAPTER 2 : ECOLOGICAL INTENSIFICATION WITH SOIL HEALTH PRACTICES DEMONSTRATE POSITIVE IMPACTS ON MULTIPLE SOIL PROPERTIES: A LARGE-SCALE FARMER-LED EXPERIMENT

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Abstract

Improving soil health is critical to reversing trends of soil degradation and is of increasing interest to a range of stakeholders including policymakers, agricultural industry leaders, food companies, and farmers. Crop and soil management practices focused on ecological functions can be effective in restoring fundamental biological, chemical and physical soil properties. The call for ecological intensification of agricultural systems has the potential to improve soil health and input-use efficiency. In this study, we developed a framework to classify spatial and temporal ecological intensification with soil health practices: tillage, crop rotation, cover crop, organic amendment, and crop-livestock integration. We applied this framework in a statewide soil health project featuring collaboratively designed on-farm research. We found that ecological intensification affected all properties commonly used in soil health assessments, but the sensitivity of different practices to impact changes varied among the soil physical, chemical and biological properties. The use of cover crops had the greatest impact on driving changes in soil properties, in particular those closely related to organic matter and carbon (C) and nitrogen (N) dynamics. Soil-test biological activity and its association with soil-test predicted N release in cropping systems intensified with cover crop use was found to reduce predicted nutrient fertility needs substantially compared to less intensified systems. Evaluating the potential of existing agricultural systems to undergo ecological intensification at a farm scale provides insights about management options to enhance soil health, particularly in regards to nutrient cycling, biological activity, and input-use efficiency.

Keywords: Soil Health Practices; Soil Properties; Ecological Intensification; Soil management; On-farm study; Cover crop

Abbreviations: CCU, cover crop use; CDI, crop diversity index; YWSD, years without soil disturbance; OAI, organic amendment index; CL, crop-livestock integration; HSHT, Haney soil health tool; MLRA, Major Land Resource Area.

Introduction

The dominant Midwestern U.S. agricultural production systems are highly specialized and input-dependent, most often focusing on high-productivity while neglecting ecological processes such as nutrient and water cycling (Prokopy et al., 2020; Gliessman, 2014). These production systems not only contribute to the deterioration of fundamental properties of soils (Evans et al., 2020) but have also shown to be fragile and vulnerable to shocks such as extreme weather events and market fluctuations, as demonstrated by the COVID-19 global pandemic (Hart et al., 2020; NOAA, 2020a, 2020b; Westhoff et al., 2020). Incorporating principles of soil health – maximizing aboveground diversity, providing continuous roots and cover of the soil, and minimizing soil disturbance – is another approach to land management; utilizing these principles on agricultural lands is widely recognized as an opportunity to recouple ecological processes, improve the production capacity of agricultural lands, and reverse trends in soil degradation (Delgado et al., 2011). Ecological intensification is proposed as a related approach to land management that incorporates “ecological processes into soil and crop management strategies to enhance ecosystem service delivery and reduce external inputs” (Bender et al., 2016).

Enhancing ecological intensification spatially (e.g., diversified crop rotations) or temporally (e.g., long-standing cover cropping, no-tilling) has been found to provide beneficial effects on ecosystem processes (Bender et al., 2016). Also, incorporating principles of soil health provides farmers with strategies to maintain productivity while reducing negative environmental impacts. For example, cover crops can reduce off-site nutrient flow and increase infiltration (Basche and DeLonge, 2019; Taylor et al., 2016), diverse crop rotations can interrupt weed growth cycles lowering pesticide use (MacLaren et al., 2019), and prescribed grazing practices, such as adding legumes and avoiding overgrazing, can protect soil and water resources (Rakkar and Blanco-Canqui, 2018; DeLonge and Basche, 2018).

There is increasing interest in promoting soil health as a solution to many agri-environmental challenges from a diverse group of stakeholders, including policymakers, agricultural industry leaders, food companies, and farmers (Sherwood and Uphoff, 2020). Some of the recent movements and agro-environmental initiatives across the US supporting soil health include the creation of the Soil Health Institute (Soil Health Institute, 2018), the initiation of the Soil Health Division by the Natural Resources Conservation Service (NRCS), the formation of the “Healthy Soils – Thriving Farms Challenge Area” by the Foundation for Food and Agriculture Research (FFAR) as well as numerous other state, local and NGO soil health incentive programs (Karlen et al. 2019). Despite increasing enthusiasm for and attention toward soil health related practices, utilization of soil health practices are still low; for example it is estimated that less than 30% of cropland acres in the U.S. utilize no-till management and 4-5% utilize cover crops (Seifert et al., 2018; USDA-NASS, 2019). Thus, this limited adoption rate raises opportunities for further advancement in research to understand the opportunity for management to improve key soil health related functions.

Emerging interest in soil health has increased the urgency to understand the potential benefits of farmers transitioning from conventional towards more ecologically-based production systems. This transition to soil health related practices can be identified in a continuum, ranging from annual crop systems with highly disturbed soils (i.e., intensive tillage, limited crop diversity) to perennially-based systems with less-disturbed soils (i.e., pasture, restored prairie) (Karlen et al., 2019). Further, farmers adopting conservation practices generally work in a whole-farm systems approach, fine-tuning and incorporating multiple elements of crop and soil management practices (Church et al., 2020). In addition, innovative farmers are interested in more systems-level experiments that incorporate multiple factors of management practices (e.g., crop rotation, cover crop, tillage methods, fertilizer application rate, time and placement) and the manner in which if one factor is implemented it influences the outcome from each of the other factors (Basche and Roesch-McNally, 2017). This suggests that analyzing soil properties in the traditional manner (i.e., individual measurement responses to single treatment factor) using small plot research are not optimal, because they have trouble evaluating more than two or three factors at once. Thus, new agronomic research methods are in need to scale up farmer's adoption of soil health practices.

Changes in physical, chemical, and biological soil properties are complex and variable. For example, soil aggregate stability, infiltration rates, and microbial indicators quantified by meta-analysis are shown to be very responsive (1-3 years for changes detection) to changes in cover crop and no-tillage adoption (Stewart et al., 2018). Other soil indicators, such as organic carbon accumulation, might require over five years to detect significant changes due to management interventions that reverse soil degradation (Angers & Eriksen-Hamel, 2008). In addition, the lack of studies jointly analyzing a range of agricultural management practices, particularly beyond small field-experiment scales, has hampered the development of a holistic approach to land management, which is important to intervene with protection and conservation strategies. To this point, a growing body of research examining current soil health assessments addresses one soil or crop practice (e.g. tillage, cover crop, organic production) at a time (de Paul Obade and Lal, 2016; Roper et al., 2017; Villamil et al. 2008; Xue et al., 2019; Zuber et al, 2017). Studies trying to differentiate among the effects of various soil management practices suggest results are inconclusive or site-specific (Roper et al., 2017; Chahal and Van Eerd. 2018; Morrow et al., 2016). However, the effect of management on soil health, which is crucial for multiple soil functions, are mostly derived from highly controlled experiments, which tend to be over-simplified in terms of system complexity (Whalen et al., 2003; Congreves et al., 2015; Alhameid et al., 2017; Nunes et al., 2018). Recent data analyses from on-farm studies considering multiple soil health practices concluded that crop diversity, tillage reduction, and the use of organic amendments are key practices for building soil health (Williams et al., 2020). However, there is a need to refine future studies by including a broader spectrum of management practices, particularly at the farm-scale.

In this research, we developed a framework to classify spatial and temporal ecological intensification of management practices included in a series of farmer-led soil health experiments. By using the concept of ecological intensification, we describe agronomic management practices (e.g. tillage, crop rotation, cover crop, organic amendment, and crop-livestock integration) based on their potential to promote crop growth and reduce soil disturbance (Caudle et al., 2013). We then employed this framework with a dataset of soil biological, chemical and physical properties from a statewide soil conservation program featuring collaboratively designed on-farm research to evaluate the impacts of management systems intended to improve soil health.

Our research questions include:

1) What is the relationship between ecological intensification and soil properties?

2) How does ecological intensification influence physical, chemical, and biological soil properties?

3) What is the relationship between nutrient recommendation and savings and ecological intensification?

Materials and Methods

Study sites and soil management systems description

This study was part of a larger, state-wide partnership to monitor changes of soil properties through the adoption of conservation practices including reduced tillage, cover crops, diversified crop rotations, and crop-livestock integration. This collaborative project was launched in 2016 through a partnership between the University of Nebraska-Lincoln (UNL) On-Farm Research Network and the U.S. Department of Agriculture Natural Resources Conservation Service, and 17 farmer collaborators (Krupek et al., 2019a, 2019b). In the first year of farm enrollment, NRCS field officer and UNL extension personnel worked with the farmer to select the field, the soil health management practice to be trialled, and to design the trial. Trials require at least an 8-hectare field (to obtain at least a 0.3-hectare minimum plot size), and the most common layout was an 8-strip or 12-strip format (n = 4 or n=6 for each treatment). The treatment strips were designed in completely randomized blocks or alternated between treatments across the field. Farmers participating in the project compared at least two contrasting soil management practices for 5 years. The selection of treatment comparisons was based on research questions generated by the farmer based on their resource concern. Guidelines followed the "farmer-initiated" approach to research, which is commonly used in on-farm research programs (Thompson et al., 2019).

Ten on-farm study sites were included from the counties of Greeley, Howard, Merrick, Colfax, Otoe, Nemaha, Knox, Dodge, Stanton, and Seward in Nebraska (Figure 2.1). Sites fall within five different Major Land Resource Area Map Unit (MLRA), which are geographically associated land resource units according to USDA-NRCS (1981) classification. On-farm sites were located in areas with a varied range of soil textures (Figure 2.2), classified predominantly as Mollisols and a few sites as Entisols and Alfisols (Supplementary Table S1) (Soil Survey Staff, 1999). Field history represented a range of soil health management practices in terms of cash crop diversity, cover crop use, soil disturbance, application of organic amendments, and mixed livestock and cropping enterprises. Such practices fall within the principles of soil health, which emphasizes reducing soil disturbance, extending periods of living roots in the soil, as well as maximizing crop and livestock diversity (USDA–NRCS, 2018).

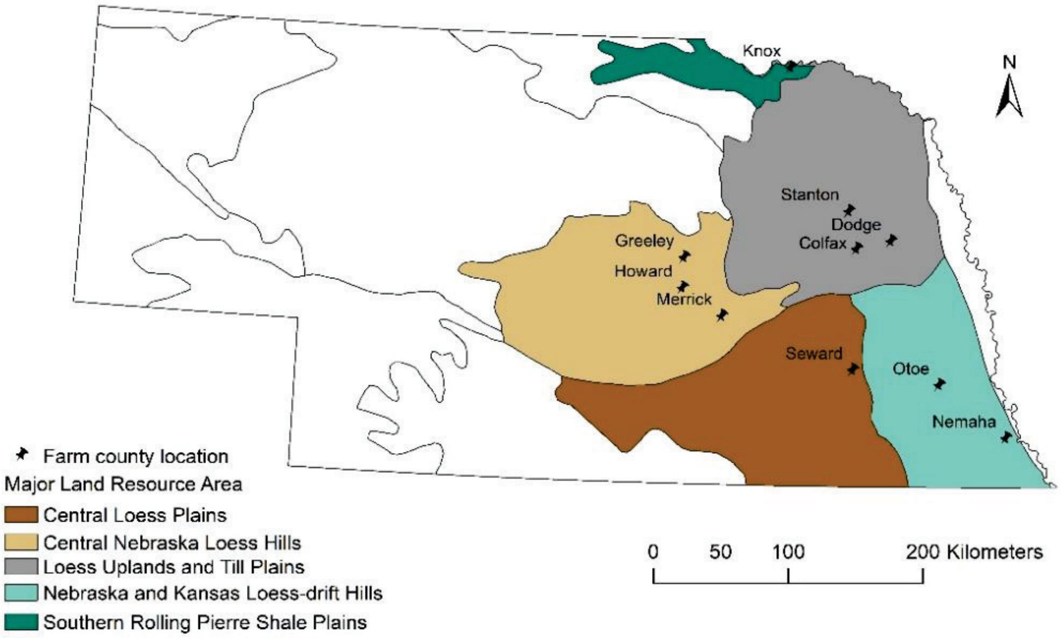

Figure 2.1 Map of on-farm trials located in five Major Land Resource Area (MLRA) in Nebraska. Farm locations are indicated by pin signs.

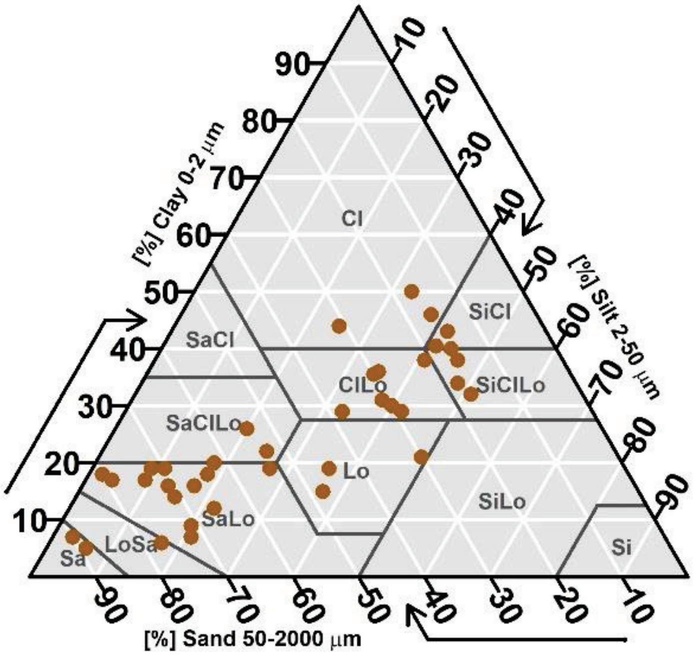

Figure 2.2 Soil texture for each of the soils sampled in this analysis, displayed in a texture triangle.

The main cash crop species included in the on-farm experiments were corn (Zea Mays L.) and soybean (Glycine max (L.) Merr.). Different small grain crops were included in some the fields, such as wheat, triticale, millet, and oats, which functioned as either cash crops, as non-grazed cover crops (with seed harvested for income), or as forage crops grazed by cattle depending on the operation. In some fields where crop-livestock integration was not part of the main treatment comparison, cattle grazed corn and wheat residues during autumn to reduce high residue loads that can hinder planting and early seedling growth in subsequent crops. All fields were managed by the farmers according to best management practices, resulting in variation in cattle stocking rates and organic and agrichemical inputs used between rotations and over time. Cereal rye (Secale cereale L.) cover crop was commonly used in sites testing single species cover crops as a treatment. However, the majority of farmers used mixtures (5+ species) of cool-season small grain cereals, legumes, brassicas, and warm-season summer annual grasses based on NRCS cover crop guidelines (USDA-NRCS, 2011). Information regarding crop rotation, soil management practice comparison, organic amendment, tillage use, and crop-livestock integration was collected annually for each field through a research participation form (Supplementary Table S1).

Classification indexes for ecological intensification of soil health practices

The diversity of soil health practices applied at the on-farm experiments reflects a continuum of management from less to more ecologically intensified cropping systems as defined in Bender's et al. (2016) framework (Figure 2.3). For each field-site treatment, we quantified the incremental changes, in space and time, of soil health practices such as crop diversity, and frequency of mechanical soil disturbance, cover crop and organic amendment use, and crop-livestock integration proposed by Williams et al. (2020) and Tiemann et al. (2015). Across all sites, time of cover crop use varied from zero to up to twelve years and years without soil disturbance varied from zero to up to thirty years. Regarding the number of different plant species in a 5-year rotation, fields varied from two to eighteen. The crop diversity index (CDI) was calculated as a ratio between the number of different crop species used and the maximum number of crop species used across all field-site treatments considering a full cycle of crop rotation (5 years). The CDI included cash crops, cover crops, and forage crops. The cover crop use (CCU) and years without soil disturbance indexes (YWSD) were quantified based on the number of years farmers were cover cropping and no-tilling, respectively. Finally, we defined organic amendment use (OAI) and crop-livestock integration (CL) as the number of applications of organic amendment and frequency of livestock grazing crop residue and cover crops during the past five years. Each index (i.e., a proxy for either length of time or intensity of soil health management) was defined to represent a progression to a more ecologically intensified cropping system due to the adoption of soil health management practices (Table 2.1). Higher index values represent higher the number of different plant species in the rotation, greater the number of years with continuous living roots, the fewer number of years with tillage operation, increased number of organic amendment applications, and more frequent integration of livestock into cropping systems.

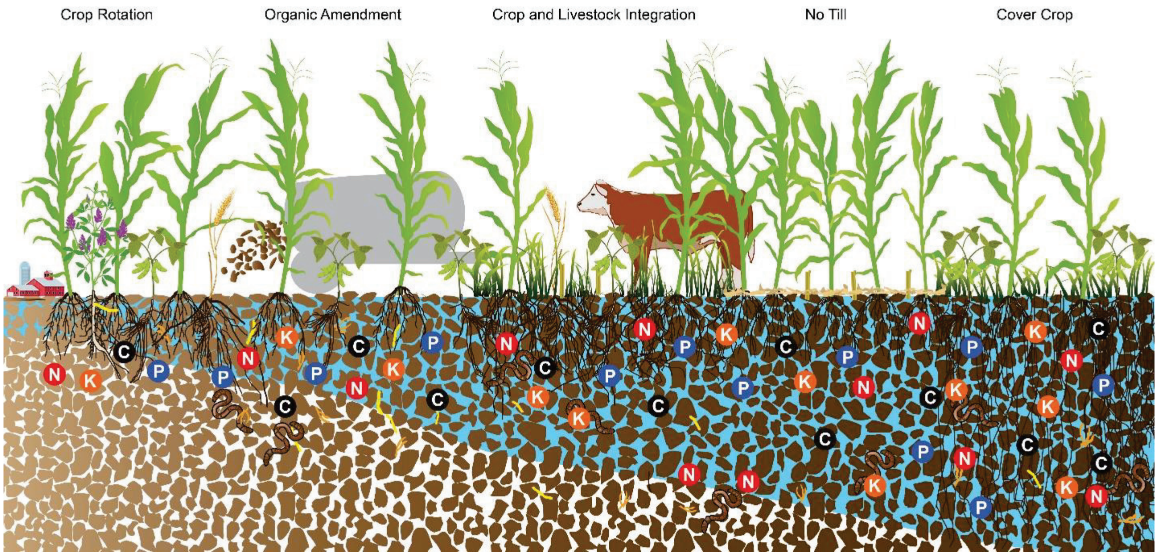

Figure 2.3 Representation of the soil health practices used in the ecological intensification framework. Practices included in this analysis were no-till, crop rotation, organic amendment, crop-livestock integration, and cover crop. Spatial or temporal intensification of these practices could lead to changes in soil physical, chemical, and biological properties. Possible changes in soil physical properties are represented through porosity or compaction (distribution of soil aggregates) and water infiltration (depth of water in the soil profile). Possible changes in soil chemical properties are represented through the addition of nutrients represented in the soil coloration (higher organic matter in darker soil) and circles representing available carbon, nitrogen, phosphorus, and potassium. Possible changes in soil biological properties are represented through the addition of bacteria, fungi, and earthworms in the soil profile. Cover cropping was found to be the most impactful of the practices on soil properties in our analysis and is represented by darker soil color, lower compaction and larger soil aggregates, higher nutrient availability and larger number of soil microbes. This could be a result of cover crops offering continuous living roots relative to the other practices and driving changes in water movement, organic matter, soil biological activity, and carbon and nitrogen dynamics as reported by this analysis. Sequence represents increases in relative importance of soil health practices averaged across all physical, chemical and biological properties included in the multiple linear regression analysis. Artwork by Lana Koepke Johnson.

Table 2.1 Maximum, minimum, mean, and median for the crop diversity index (CDI), cover crop use (CCU), years without soil disturbance (YWSD), OAI (organic amendment index), and crop-livestock integration (CL).

	CDI[a]	CCU	YWSD	OAI	CL
Maximum	1	1	1	0.2	1
Minimum	0.11	0	0	0	0
Mean	0.40	0.35	0.41	0.04	0.23
Median	0.36	0.33	0.33	0	0

[a] Soil management index calculation of the i^{th} field and the maximum measured value within our dataset: $CDI = \frac{CDI_i}{CDI_{max}}, CCU = \frac{CCU_i}{CCU_{max}}, YWSD = \frac{YWSD_i}{YWSD_{max}}, OAI = \frac{OAI_i}{OAI_{max}}, CL = \frac{CL_i}{CL_{max}}$

Soil sampling

Fields included in the analysis ranged from 10 to 40 ha with plot sizes ranging between 0.25 and 4.75 ha, depending on the farm field. All fields were sampled from a 0-15 cm depth in autumn 2019, two or three years after the initiation of the on-farm experiment (experiments initiated either in 2016 or in 2017). Samples from the same field were collected on the same day to avoid moisture or temperature fluctuations between sampling locations. Each sampling point was geo-located using a global positioning system (GPS).

Sampling points for soil properties analysis (conducted either in the field or in laboratory) were selected on a representative basis from the soil type, plot size, and replication (Supplementary Table S2). There was at least one sampling location within a replicate strip. To minimize spatial soil variation within a sampling location, a 6 m x 24 m area located at least 5 m away from the plot boundaries was designated for soil measurements (Supplementary Figure S1). Ten bulk soil samples, located at least 6 m apart from each other, were collected and composited for Haney test soil analysis, using a soil sampler of a core diameter of 32 mm diameter model PN012, JMC Backsaver N-2 handle (JMC Soil samplers, Newton, IA, USA). In fields with a history of banded fertilizer application, soil cores were collected from a transect perpendicular to the row crop, and if banding fertilizer was not practiced samples were collected adjacent to the cash crop row or near the rooting structure (Franzen, 2017). A total of 148 individual soil composite samples from 0-15 cm depth were collected across 30 site-soil health management comparisons. Total sampling area was 267 ha. Soil samples were stored in sealed plastic bags and transported in an ice-filled cooler to the laboratory for refrigeration at 4 °C until being shipped for laboratory analysis.

Assessment of soil properties

Soils were analyzed for 21 field and laboratory measurements of physical, chemical, and biological indicators. Field measurements included in the NRCS assessment protocol (USDA-NRCS, 2020) were soil temperature, soil porosity, and infiltration, a measure of initial water infiltration using the method described by Smith (1999). Bulk density was determined using the core method (Blake & Hartge, 1986). Gravimetric soil moisture content was determined using methods described by Gardner (1986).

The remaining chemical and biological properties were analyzed using protocol from the Haney soil health test (HSHT), including soil respiration and nutrient testing (Zuber and Kladivko, 2018). Soil-test biological activity (e.g. soil respiration, flush of CO_2) was determined from the flush of CO_2-C following rewetting of dried soil with 24-h aerobic incubation at 50% water-filled pore space and 25 °C. For analysis, 40 g soil samples in 0.25-L glass jars were wetted and CO_2-C was determined by infrared gas analyzer of headspace (Franzluebbers, 2021). Soil organic matter content was analyzed by mass loss on ignition (LOI) at 500 °C for two hours and expressed as percent LOI (Nelson and Sommers, 1996). Nutrient testing for essential plant nutrients such as inorganic nitrogen (nitrate and ammonium), inorganic, organic, and total phosphorus relied on the Haney, Haney, Hossner, and Arnold (H3A) soil extractant, a weak acid containing organic plant root exudates typically associated with plant nutrient uptake from soil (Haney et al., 2006, 2010). HSHT also includes results of water-extractable organic C and N, measures of the pool of organic carbon and nitrogen readily available to the microbes. Water extractable C fractions are the most active SOC compounds comprised of mainly carbohydrate derived from plant roots, microorganisms, amino acids and humid substances (Kalbitz and Kaiser, 2008; Ćirić et al. 2016). Thus, these fractions can contribute to SOC changes due to management being a suitable indicator for soil health assessment (Ghani et al. 2003) Other routine soil measurements included total elemental potassium, calcium, aluminum, sulfur, manganese, magnesium, and sodium analysis using inductively coupled argon plasma (ICAP) atomic emission spectroscopy.

Soil health score, soil-test predicted nitrogen release, and nutrient recommendations for the subsequent cash crop were HSHT-based calculations included in this analysis. Soil health score was calculated based on values of soil-test biological activity, water-extractable organic carbon, and water-extractable organic N (Eq. 1). Soil-test predicted N release is the total amount of N being released through microbial activity from the organic N pools. It is the product of water-extractable organic N and microbial-available C expressed in ppm (Eq. 2 and 3). The soil-test predicted N release calculation is built on the assumptions that (i) water-extracted C and soil respiration represent the total potential food source and the potentially mineralizable C, the C accessible to microbes in 24-h incubation (including physically bound C active to microbes), respectively; (ii) soil microorganisms use a similar proportion of water-extracted C and water-extracted N, (iii) during the growing season N is released in the soil, on average, four times after significant precipitation and (iv) the soil-test predicted N release cannot exceed the water-extracted organic N (Haney test interpretation guide, 2021). These HSHT calculations are evolving, but those presented here were used as of February 2020, by Ward Laboratories (Kearney, Nebraska).

$$SH_{score} = \frac{CO_2-C}{10} + \frac{WEOC}{50} + \frac{WEON}{10} \qquad (1)$$

$$Soil - test\ predicted\ N\ release = WEON * MAC * 4 \qquad (2)$$

$$MAC = \frac{CO_2-C}{WEOC} \qquad (3)$$

where CO_2-C is the soil-test biological activity, WEOC is water extractable organic C, WEON is water extractable organic N, and MAC is microbially active C.

Nutrient recommendations from HSHT for the subsequent cash crop, expressed on a per-area basis, were calculated based on nutrient concentrations extracted from soil analysis and yield goals of 10.7 and 4.0 ton/ha for corn and wheat, respectively. Recommendations were developed based on calibrations from the University of Nebraska and Kansas State University (R. Ward, personal communications, November 4, 2020 and January 20, 2021). Yield goal values were selected to represent an average attainable yield for a typical farm in Nebraska considering both irrigated and rainfed systems (USDA, 2019). Finally, soil-test hypothetical N savings were calculated based on the difference (kg/ha) in N measured using the HSHT (using water-extractable C and N pools) and traditional soil testing using residual nitrate and considering an N price of $0.91/ kg N.

Statistical analysis

In order to examine the research questions of interest, we analyzed a dataset comprised of 148 observations (i.e., composite samples) collected from ten farms. Statistical analyses were performed using the R software version 4.0.4 (R Core Team, 2018). Because multiple soil properties were measured from the same on-farm sites, there may be correlations among the variables, errors, and responses. Therefore, the first step in the analysis was to perform Pearson correlation analysis and observe how the soil properties were correlated to each other (Supplementary Figure S2). Given the moderate to high correlation among variables, which supports the usefulness of a multivariate approach, the next step was to perform a principal component analysis (PCA) to analyze the variation in soil properties and ecological intensification indexes as affected by field location. This analysis was performed based on correlation matrix, rather than the covariance matrix, because the soil health indicators included in the data set have different units and variances (Supplementary Table S3). All individual variables were checked for normality, confirming approximate multivariate normality and suitable use of linear ordination methods. We also performed multiple linear regression to analyze the influence of ecological intensification of soil health practices (i.e., classification indexes) on soil properties according to the model: y = CDI + CCU + YWSD + OAI + CL. Variance inflation factor and collinearity diagnosis were performed to confirm the absence of a strong correlation among the management indexes used as predictors (Supplementary Tables S4 and S5). Residuals of all regression models were checked for normality and homogeneity of variance. Log transformation of the dependent variable was used for infiltration and sulfur. Relative importance analysis was performed to understand the extent to which each soil health management index drives the prediction of soil properties. Relative importance (RI) was calculated and considering the R2 contribution averaged over orderings among repressors (lmg metrics) and expressed as percentage, according to Chevan and Sutherland (1991). The explained multiple regression model variance was partitioned among the predictors to understand the role played by each soil health management index in the regression equation. The PCA, multiple regression models, and relative importance analysis were performed using the functions prcomp in the package stats, stepAIC in the package MASS, and relimp in the package relaimpo (Grömping and Lehrkamp, 2015), respectively. Simple linear regression was used to understand the relationship between the variables soil-test predicted N release and soil-test biological activity as well as corn and wheat N recommendation.

Results

Soil physical, chemical and biological properties showed great variability across sites and ecological intensification with different soil health practices (Figure 2.4). The first two principal components (PC) explained 35% of the total variability within the dataset. The first PC primarily described the variation due to physical versus biological and chemical soil properties. This is illustrated in Figure 2.4 as the physical soil properties (e.g., bulk density, soil temperature, infiltration, volumetric water content) have low PC1 scores while biological and chemical properties (e.g., soil-test biological activity, soil health score, water extractable organic and total N) have high PC1 scores. Fields with higher intensification in crop diversity (CDI) were associated with greater infiltration and soil porosity, couple with reduced bulk density since the angle between CDI and these soil properties is either very small pointing towards the same direction (positive correlation) or in opposite direction (negative correlation) (Figure 2.4). Likewise, higher intensification in cover crop use (CCU) was associated with greater water extractable organic C (WEOC), soil-test biological activity, SH score, calcium, magnesium and reduced bulk density. Intensification in organic amendment (OAI) was mainly associated with greater organic matter and soil-test biological activity. Fields with higher years without soil disturbance (YWSD) were associated with greater soil volumetric water content, coupled with reduced potassium, organic phosphorus and inorganic nitrogen. Fields intensified with crop-livestock integration (CL) were associated with greater soil temperature and reduced levels of potassium, organic P and inorganic N (Figure 2.4). There was a clear separation between soil samples from the Central Nebraska Loess Hills and the rest of the MLRA. This is illustrated in Figure 2.4, as the PC scores of Central Nebraska Loess Hills were primarily in the upper quadrants while the other MRLA data points were located mostly in the lower quadrants. The loading for PC2 indicate that organic matter, volumetric water content, potassium, organic P and inorganic N were helpful in separating the MRLA regions. PC1 was a contrast of high positive loadings of CDI, CCU, water extractable organic N, organic P, potassium and soil health score against the negative loading of bulk density (Supplementary Table S6). PC2 consisted of negative loadings of CCU, YWSD, and soil health score and high positive loading of potassium (Supplementary Table S6). Taken together, results from the principal component (PC) analysis provided evidence that the different experimental sites, located in different regions and MLRAs, were diverse with regard to soil properties and intensification in CDI, CCU, YWSD, OAI, and CL (Figure 2.4). In addition, improvements in soil health through soil aggregation (reduced compaction and improved porosity and infiltration) and nutrient cycling, primarily organic C and N , were influenced by ecological intensification, particularly in CDI, CCU and OAI (Figure 2.4, Supplementary Table S6).

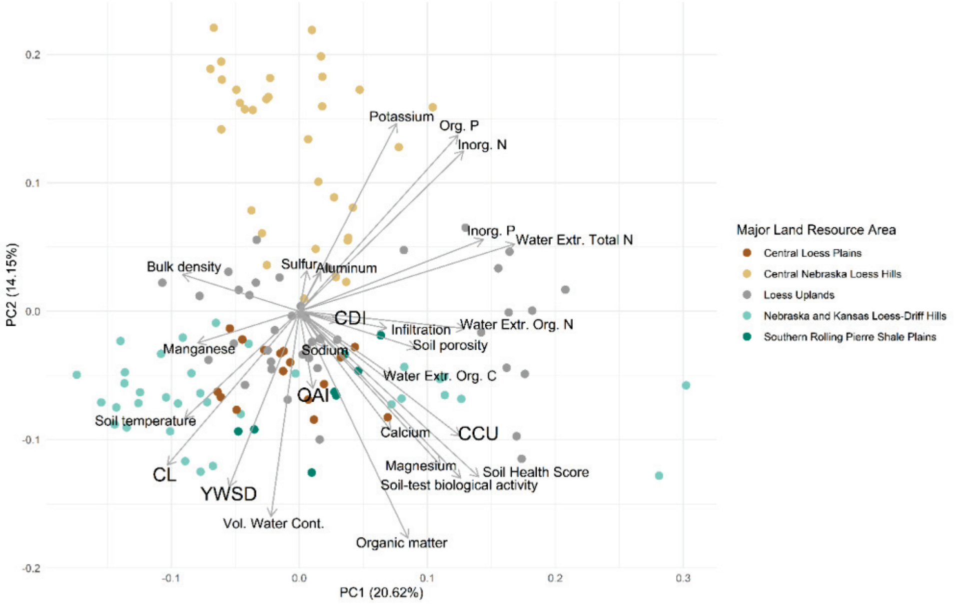

Figure 2.4 Biplot obtained from principal components analysis based on the correlation matrix, showing the two first principal components (explaining 21% and 14%, respectively). Each point represents samples collected in different fields (n=148), loadings indicate soil properties and ecological intensification indexes. Descriptors: CDI = crop diversity index, CCU=cover crop use, OAI = organic amendment index, YWSD= years without soil disturbance, CL=crop-livestock integration.

To further explore our dataset and understand the PCA results, we performed multiple regression analysis to identify the combination of practices that perform best (i.e. most important factors leading to improvements in soil properties), when ecological intensification in various soil health practices is assessed simultaneously. This overcomes the constraints of previous research studies that usually evaluate only two to three management factor at once (such as no-till vs. conventional tillage, continuous corn vs. crop rotation or moderate vs. intensive vs. no grazing). We tested different random effect models to account for the three main sources of random variation in our study block, farm location and region (MLRA), but this did not significantly change the regression coefficient, slopes or the relationships between soil properties and ecological intensification indexes presented here (not shown). Additionally, we tested but did not add interactions to the model because they could result as an artifact of the varied indices across all experiments (not every index/soil health practice was included at every site) rather than resulting from any biological process or meaning. Thus, we considered it impractical to include all potential interactions knowing that the biological meaning of this inclusion was limited.

Results from multiple linear regression analysis showed that soil physical, chemical and biological properties were all significantly affected by site-specific ecological intensification, but the effects of ecological intensification on building healthy soil is practice- and soil property-specific (Table 2.2). Soil properties were either positively or negatively related to different ecological intensification, and the regressions yielded multiple R^2 values between 0.07 and 0.79 (Table 2.2). For example, as intensification in CCU and OAI increased, soil water infiltration, organic matter content, soil respiration (i.e. microbial activity), organic and inorganic P, and soil health score increased. Conversely, some soil health indicators were negatively correlated to intensification in soil management. For example, a high YWSD was associated with improvements in soil water infiltration but decreases in soil organic matter, water-extractable organic C and N, and soil respiration (Table 2.2). Further, analysis of regression equation coefficients showed that soil properties were influenced via different paths by intensification in soil health management. For example, CCU was the most important and only soil management practice identified by the multiple regression analysis that lead to increases in both organic (i.e. water-extractable organic and total N) and inorganic N (Table 2.2).

Table 2.2 Average coefficients for the predictors of changes in soil properties based on multiple linear regression model y = CDI + CCU + YWSD + OAI + CL, as well as the R2, i.e. the variance that explained by the regression model. Intercept is the intercept of the linear mixed-effect regression model; CDI, CCU, YWSD, OAI, CL are the ecological intensification indexes for crop diversity index, years of cover crop use, years without soil disturbance, organic amendment index, and crop and livestock integration.

Soil properties		Soil ecological intensification index[a]					
	Intercept	CDI	CCU	YWSD	OAI	CL	R^2
NRCS			Slope coefficients				
Infiltration (mm/hour^{-1})[b]	2.87^{***}	1.08^{*}	1.64^{***}	0.27^{ns}	-4.44^{**}	-0.07^{ns}	0.20^{***}
Soil porosity (%)	55.27^{***}	0.40^{ns}	2.85^{ns}	-1.90^{ns}	4.77^{ns}	-4.29^{***}	0.19^{***}
Soil temperature (°C)	3.07^{***}	-0.48^{ns}	-1.60^{**}	2.65^{***}	7.97^{***}	5.11^{***}	0.79^{***}
Volumetric water content (%)	20.21^{***}	8.29^{***}	-0.23^{ns}	10.30***	-12.14*	-3.44^{*}	0.32^{***}
Bulk density (g cm^{-3})	1.21^{***}	-0.04^{ns}	-0.09^{ns}	0.01^{ns}	-0.16^{ns}	0.13^{***}	0.17^{***}
HSHT							
Water Extr. Org. N (ppm)	12.96^{***}	-5.16^{***}	7.68^{***}	-5.23^{***}	-0.51^{ns}	-1.25^{ns}	0.62^{***}
Water Extr. Org. C (ppm)	162.20^{***}	-37.16^{*}	45.04^{**}	-46.38^{**}	57.35^{ns}	9.74^{ns}	0.08^{**}
Water Extr. Total N (ppm)	22.25^{***}	-9.52^{***}	19.59^{***}	-5.60^{**}	-8.29^{ns}	-5.81^{***}	0.59^{***}
Organic matter (% LOI)	3.07^{***}	-0.50^{ns}	1.81^{***}	-0.56^{ns}	3.43^{***}	0.66^{**}	0.27^{***}
Soil-test bio. activity (ppm CO_2)	38.27^{***}	-4.84^{ns}	43.90^{***}	-19.59^{*}	88.34^{***}	6.94^{ns}	0.22^{***}
Inorganic N (ppm)	11.12^{***}	-1.12^{ns}	8.01^{***}	-1.65^{ns}	-12.51^{*}	-5.79^{***}	0.37^{***}
Inorganic P (ppm)	13.53^{***}	-5.22^{ns}	16.06^{***}	-4.12^{ns}	45.56^{***}	-9.80^{**}	0.32^{***}
Organic P (ppm)	5.76^{***}	-1.41^{***}	0.74^{ns}	-2.29^{***}	3.55^{**}	-1.43^{***}	0.60^{***}
Potassium (ppm)	115.35^{***}	11.42^{ns}	-22.48^{ns}	-12.16^{ns}	-119.23^{*}	-27.94^{*}	0.13^{***}
Calcium (ppm)	459.06^{***}	-70.93^{*}	7.89^{ns}	-59.63^{*}	538.87^{***}	167.92^{***}	0.46^{***}
Aluminum (ppm)	219.20^{***}	-64.10^{***}	61.33^{***}	-54.47^{***}	286.97^{***}	-0.50^{ns}	0.46^{***}
Sodium (ppm)	18.28^{***}	1.70^{ns}	-2.41^{**}	-3.77^{***}	4.03^{ns}	-0.02^{ns}	0.51^{***}
Manganese (ppm)	3.05^{***}	1.56^{ns}	-2.99^{***}	7.51^{***}	-15.64^{***}	-0.01^{ns}	0.56^{***}
Magnesium (ppm)	92.94^{***}	-5.90^{ns}	66.60^{***}	-48.91^{***}	148.08^{***}	18.81^{*}	0.30^{***}
Sulfur (ppm)[b]	1.79^{***}	0.40^{ns}	-0.38^{*}	-0.07^{ns}	3.73^{***}	-0.91^{***}	0.48^{***}
Soil health score	8.10^{***}	-1.98^{*}	6.38^{***}	-2.96^{***}	9.48^{***}	1.06^{ns}	0.31^{***}

[a] CDI, CCU, YWSD, OAI, CL are the crop diversity index, years of cover crop use, years without soil disturbance, organic amendment index, and crop and livestock integration.

[b] Regression coefficients presented for infiltration and sulfur are based on relationship between the regression predictors and log transformed response variable.

ns,*,**,*** indicates not significant and significant regression coefficients at $p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively.

The contribution of management intensification to the different soil properties was quantified with relative importance analyses (Figure 2.5). With respect to soil properties that are closely related to C and N dynamics such as soil respiration, organic matter, water-extractable organic C, N, total N, and soil health score, CCU explained 67, 68, 34, 39, 59, and 70% of the total variance, respectively (Figure 2.5). The highest relative importance of CDI was observed for soil water infiltration and volumetric water content, with 77% and 23% respectively, CCU was observed for soil respiration and organic matter with 78 and 68%, respectively. Likewise, the highest relative contribution of YWSD was observed for manganese with 62%; OAI was observed for sulfur and aluminum with 57% and 46%, respectively; and CL was observed for bulk density and soil porosity, contributing to up to 59% of the variance explained. Averaged across all soil physical, chemical and biological properties, CCU was the most important and contributed 31% to the overall influence of all assessed properties, followed by YWSD, CL, OAI, and CDI (Figure 2.5). Considering all the ecological intensification indexes used in this analysis, CCU is the only one that features continuous living cover and roots in the soil with cover cropping.

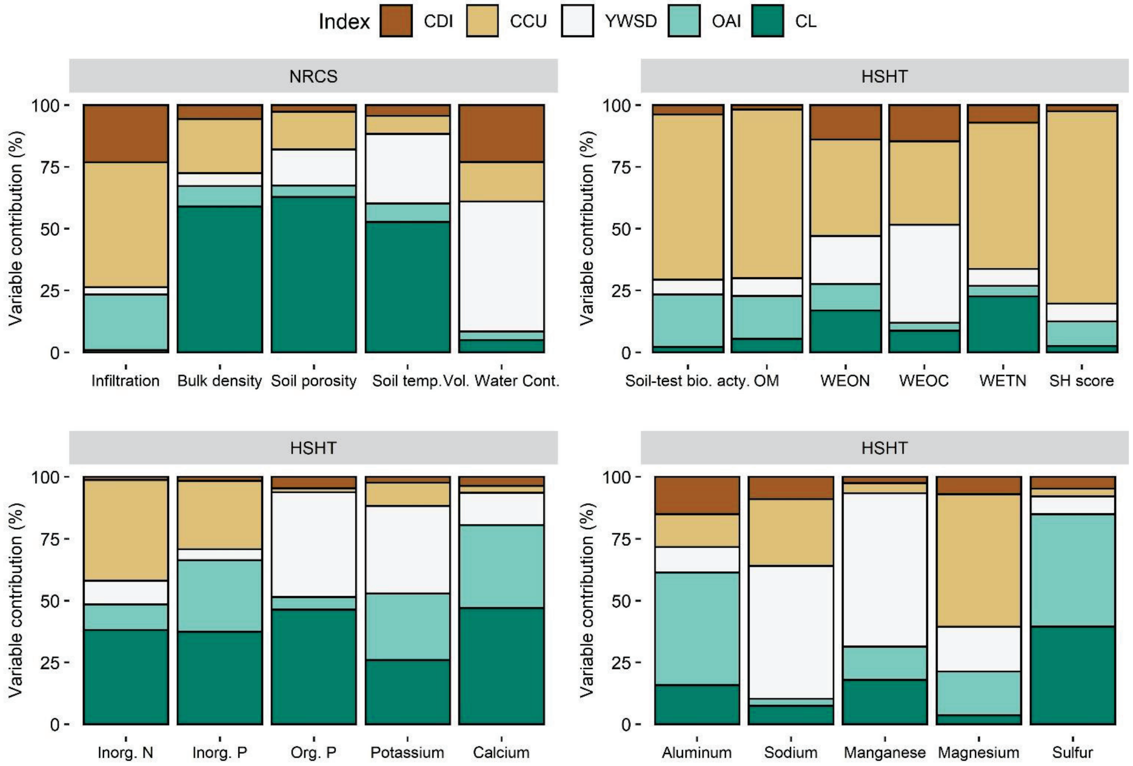

Figure 2.5 The relative importance of crop diversity index (CDI), years of cover crop use (CCU), years without soil disturbance (YWSD), organic amendment index (OAI), and crop-livestock integration (CL) on physical, chemical and biological properties used in the multiple linear regressions shown in Table 2. Descriptors: Soil temp. = soil temperature, Vol. water content = volumetric water content, Soil-test bio. acty. =soil-test biological activity, WEON = water-extractable organic nitrogen, WEOC = water-extractable organic carbon, WETN= water-extractable total nitrogen, OM = organic matter, SH score = soil health score, Inorg. N = inorganic nitrogen, Inorg. P = inorganic phosphorus, Org. P = organic phosphorus.

As a hypothetical estimate of soil N supply, soil-test predicted N release (mineralizable N considering a 24-h soil incubation) was highly associated with soil respiration (Figure 2.6a). Further, our analysis showed that intensification in CCU resulted in greater soil-test biological activity and soil-test predicted N release (Figure 2.6a). The results of the relationship between HSHT calculations of plant-available N show that organic N release was found to be negatively correlated to corn and wheat N recommendations (Figure 2.6b and C). Organic N release is an overall N credit the HSHT measures from the soil that the more conventional fertility tests utilizing only nitrate or ammonium do not account for. Because organic N release is the amount of N being released through microbial activity from organic N poll, this value typically increases as the soil system gets healthier. In our analysis, we found that in healthy and high functioning biologically active soils, particularly those with high intensification in CCU, this organic N release credit could be above 10 ppm and reduce N fertility needs substantially. On the other hand, this credit can also be minimal and may not have an impact on the amount of fertilizer required in soils that are deemed as less healthy, for example, those with low intensification in CCU (Figure 2.6b and 6c).

Finally, our results of soil-test hypothetical N savings showed that fields adopting cover crops for over eight years ($CCU \geq 0.66$) could save on average \$44/ha in N application (Figure 2.6d). Likewise, fields with low intensification in CCU ($CCU < 0.66$) could save less than intensified fields, on average \$32/ha (Figure 2.6d). These values represent the potential amount (\$/ha) saved on N application based on the difference in the N results between HSHT (using organic N pools) and traditional soil test (using nitrate). Taken together, these results suggest that predicted N fertilizer recommendations could be reduced when organic N pools are considered as a way to capture a greater potential nutrient pool than standard soil testing. The addition of a cover crop was also found to enhance carbon inputs and facilitate biologically active N cycling. Farmers adopting intensified management practices to improve soil health, particularly related to long-term cover cropping, can lead to lower requirements for predicted N fertilizer input and higher savings when organic nutrient pools are considered in fertilizer recommendations.

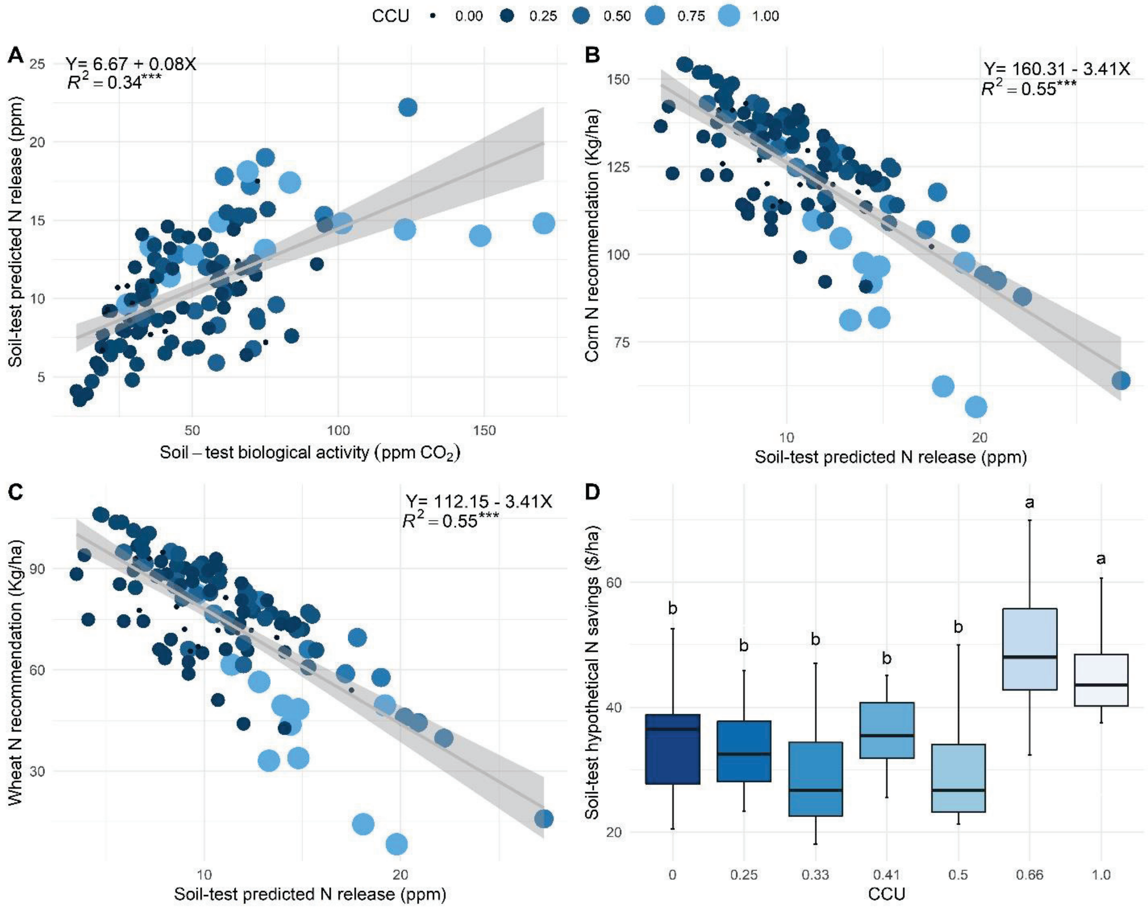

Figure 2.6 Relationship between soil-test biological activity and soil-test predicted nitrogen release (A), soil-test predicted nitrogen release and corn N recommendation (B), soil-test predicted nitrogen release and wheat N recommendation (C), and cover crop use index (CCU) and soil-test hypothetical N savings. Nutrient recommendation, variables calculated in the HSHT, considered a yield goal of 11.71 and 4.44 US ton/ha for corn and wheat respectively. N savings is the difference in the amount of N (kg/ha) measured between the Haney Test (HSHT) and traditional soil test using nitrate and considers a price of $0.91/kg N. N savings for a given CCU indicated by the same lower-case letter are not significantly different at p=0.05 level. Circle size represents cover crop use (CCU) index, a higher CCU represents greater number of years of cover crop adoption.

Discussion

Describing variation and association between ecological intensification and physical, chemical, and biological soil properties

Our study included on-farm trials with a diversity of soil health management practices that are possible alternatives to the shift from conventional to more ecologically-based production systems in Midwestern U.S (Figure 2.3). Cropping systems have changed throughout the most recent decades in our study region; landscape complexity shifted from high diversity in the 1950s and 1960s, with corn (Zea mays L.), sorghum (Sorghum bicolor [L.] Moench), alfalfa (Medicago sativa L.), wheat (Triticum aestivum L.), oats (Avena sativa L.), and soybean (Glycine max [L.] Merr.) to maize-dominated systems comprising the current landscape (Hiller et al., 2009). However, farmers in our study region have shown increased interest and adoption of soil health management practices such the addition of cool-season cash crops, no-till, and cover crops in the last decades (Knowler et al., 2007; Baumgart-Getz et al., 2012). The wide adoption of glyphosate-resistant crops contributed to the increase in no-till or reduced-till systems in Midwestern US (Givens et al., 2009). Additionally, over the last decade, intensification of the corn-soybean rotation has occurred through drilling multi-species mix cover crop after main crop harvest or interseeding cover crop prior to main crop harvest (Oliveira et al., 2019). There are, therefore some distinct differences in farmer’s adoption timing for soil health practices between our study and studies carried out in other parts of the world. Low crop diversity in our study is represented by 1-2 different crops (primarily corn and soybeans) whereas a high crop diversity meant up to six different species within a five-year rotation. Cover crops on farms for over a decade represent a long amount of time for farms in eastern Nebraska. Farmers in our study region using no-till systems for two to three decades, particularly after the introduction of glyphosate-resistant crops in 1996 (Duke and Powles, 2008), is common.

This study was conducted using a dataset of soil biological, chemical and physical properties from a statewide soil conservation program featuring collaboratively designed on-farm research. We did not compare two to three management factors at once (no-till vs. conventional tillage, continuous corn vs. crop rotation or moderate vs. intensive vs. no grazing) as many previous traditional replicated field experiments using standard statistical designs. Instead, our proposed ecological intensification framework assessed various soil health practices simultaneously to identify the combination of practices that leads to improvements in soil properties. The on-farm design of the study and farmer-reported soil testing also made it possible to include evolving calculations linking soil biology with soil fertility, soil health and farming inputs. The results presented and discussed in the following sections are informative from a scientific perspective as it offers greater potential for enhancement of farmer's knowledge of the soil system and could be beneficial for making improvements in farm management decisions (Rhymes et al., 2021).

Agricultural management gradients representing incremental changes in soil health-promoting practices are often more difficult to evaluate (i.e., detect treatment differences) than those involving sharply contrasting practices. However, understanding soil processes and quantifying changes in these transitions to more ecologically-based production systems are critical steps to provide farmers information to support their management decisions and to quantify the benefits of these soil conservation practices. Research in soil health traditionally has focused only on one management practice at a time comparing highly contrasting treatments under controlled conditions (Rojas et al., 2016; de Paul Obade and Lal, 2016, Campbell et al., 1998). This approach of using traditional replicated field experiments often ignores the role of farmers' preference for management practices and/or implementation timelines and raises questions on less contrasting situations reflecting an agricultural management gradient towards ecologically-based farming practices. The PCA demonstrates the variables and soil processes that are more impactful in differentiating the transition toward ecologically-intensified soil management practices (Figure 2.4). The relatively low percentage of the variance explained by the first two PCs underscore the complexity of the system in this transition to utilizing more soil health related practices, with many possible feedback loops derived from soil function and processes. This also implies the existence of other factors that could affect soil properties in ecological intensification.

CCU, CDI, and OAI were the indexes featuring temporal intensification in continuous living cover and roots in the soil, spatial diversification in quantity and quality of the crop residue, and addition of external organic inputs over time, respectively. Physical soil properties such as infiltration and bulk density were strongly related to CCU, CDI, and OAI (Figure 2.4). The soil-test biological activity, organic matter, and water-extractable organic C and N were also indicators associated with these indexes and very important for soil biological activity and C and N dynamics. These results are consistent with previous findings including meta-analyses documenting increases in soil carbon, microbial biomass, and organic matter dynamics in response to cover crops and crop rotation (McDaniel et al., 2014a, 2014b; Poeplau and Don, 2015). Improvements in water cycling with the adoption of cover crops, which maximize soil cover and period with roots in the system, was also found in a meta-analysis evaluating infiltration rates with different soil health related practices (Basche and DeLonge, 2019). Another important finding in our analysis is the negative loading of high bulk density being displayed in the opposite direction of the indexes CCU, CDI, and OAI (Figure 2.4). Low bulk density with increased intensification with cover crop, crop diversity and organic amendment is possibly attributed to the high organic matter and the presence of continuous roots in soils, with reduced disturbance and maximized periods without roots (Rojas et al., 2016).

As previously described by Zuber et al. (2017) and McDaniel et al. (2014a), the influence of crop rotation on soil health varies according to the specific crop species selected in the rotation. The high association between CCU and CDI and chemical properties such as sodium, calcium, magnesium, organic C, and N are most likely associated with the quantity and quality of the crop residue and the fertilizer management program adopted depending on the species in the rotation (Figure 2.4). The observed association between OAI and soil properties such as soil porosity, organic matter, water-extractable organic C and N was associated with improved soil structure and nutrient retention (Figure 2.4). As observed in previous findings, manure application increases aggregate stability and retention of applied nitrogen (Gardner and Drinkwater, 2009; Jiao et al., 2006; Wortmann and Shapiro, 2008). In addition, the high C and N loads in the PC also observed by Rojas et al. (2016), where total organic C and N were found to be the most sensitive chemical soil properties when using multivariate statistical techniques in deforested areas for agricultural use. Organic C and N are related to multiple soil properties such as soil texture, pH, cationic exchange capacity, soil aggregation, nutrient storage, and supply, being critical in multiple soil processes and commonly used as a soil health indicator (Reynolds et al. 2002; Govaerts et al., 2006).

The YWSD index describes the temporal soil disturbance through tillage operations. Regular soil disturbance caused by tillage practices causes direct changes on soil structure and pore space, which alter soil hydrologic properties (Pires et al., 2017; Kay and Vanden Bygaart, 2002). For example, improvements in aggregate stability, saturated hydraulic conductivity, and available water capacity have been quantified by meta-analyses in response to conservation tillage practices such as no-till, ridge-till, and mulch-till (Li et al., 2019). We found that volumetric water content, soil temperature, and organic matter were strongly related to YWSD, suggesting a change in soil structure and organic C dynamics with intensification in YWSD (Figure 2.4). Recent study using X-ray computer tomography, a cutting-edge technology to access soil pore space, found that conventional tillage reduces near-surface (0-5 cm) soil organic matter by increasing pore anisotropy (i.e., degree of dissimilarity in orientation) and total macroporosity. Conversely, in the same study, no-tillage increased near-surface (0-5 cm) soil organic matter by increasing soil aggregate stability and pore connectivity (Guo et al., 2020).

Macropores play a role in water infiltration and drainage (Ferro et al., 2013). The pattern observed in the PCA suggests a combination of near (0-5cm) and below (>5cm) surface effects of low YWSD on soil organic matter and hydrological properties once soil natural permeability is altered by mechanically disturbed fields (Parra et al., 2011; Sanzano et al., 2005).

The multiple regression analysis takes a different approach in evaluating how incremental changes of the practices - crop diversity, avoidance of mechanical soil disturbance, use of cover crop, application of organic amendments, and crop-livestock integration - impact on soil properties (Table 2.2). Our results show that the effects of these different management practices do not always follow the same trend in terms of their impacts on soil health, indicating that combining the effects into a single index may not be appropriate to understand its effects on soil properties. In addition, as highlighted by Williams et al (2020) in their approach, knowledge of the interaction between soil health management and soil properties is lost when focusing on a single soil management composite index.

By studying multiple soil management practices and not integrating the practices into a single index via the multiple linear regression models, our results show slightly different patterns than other studies based on long-term plot experiments with highly contrasting treatments. For example, YWSD was negatively related to soil-test biological activity (CO2-C), organic matter, total N, and water-extractable organic C and N, indicating that the longer the years without soil disturbance by tillage practices, the lower the values for these soil properties related to organic matter and C and N dynamics (Table 2.2). In contrast to our findings, studies across soil textural classes found that no or reduced tillage increase near-surface (0-5cm) stocks of organic C and N and respired CO2-C (soil respiration) in the long term (> 20 years) (Mikha & Rice, 2004; Hermle et al., 2008; Kaiser et al., 2014). These reported near-surface increases were associated with a great amount of crop residue in the soil surface, improved physical protection of OM against microbial decomposition due to occlusion in aggregates, increase OM mineralization, and greater microbial abundance under no-tillage systems (Balota et al., 2004; Kaiser et al., 2014).

The most likely explanation for the contradictory results between our findings and the literature is related to the sampling depth adopted in our soil health assessment (0-15 cm depth), which may have caused a dilution effect for C and N on the surface and sub-surface under long term reduced soil disturbance. Also, our approach did not differentiate between tillage types (e.g. mouldboard ploughing, chisel ploughing, disc harrowing) or accounted for tillage depths (e.g. various forms of reduced tillage). As opposed to near-surface, greater CO2-C emissions and labile organic C and N pools were observed under conventional tillage for sub-surface soil (5-25 cm). This corroborates our findings and can be explained by the transfer and redistribution of fresh plant residues from the soil surface to greater soil depths under conventional tillage and also by the percolation of dissolved OM from the surface into the sub-surface soils (Kaiser et al. 2014). Thus, tillage effects on soil functions related to organic matter dynamics are soil depth-specific (Kaiser et al., 2014; Blanco-Canqui et al., 2021), suggesting the importance of standardized sampling depths when considering multiple soil properties and the need for deeper soil sampling to fully understand the impact of soil disturbance on soil organic C dynamics.

Our results show that regression models considering multiple practices could explain as much as 79% of the variation in our data (Table 2.2). Our results are consistent with findings reported by Williams et al. (2020) using on-farm data from outside the USA and considering a range of soil health-building practices. Some of the remaining variations in our dataset could be a result of other factors such as climate (precipitation and mean annual temperature), dry mass above-ground plant residue retained, or other soil management that were not included in the analysis.

Cover crop effects on biological properties and nutrient use efficiency

Despite variation in sensitivity of how ecological intensification affected soil properties, cover crop use (CCU) was found to be the most impactful soil health practice, particularly on properties that are closely related to organic matter and C and N dynamics (Figure 2.5). The identification of soil management practices that not only improve crop yield but also enhance ecosystem efficiency is critical for the determination of soil health (Arshad and Martin, 2002; Lal, 2013). Practices that promote continuous living roots into the soil, such as the use of cover crops, can help to capture nitrogen in the soil and reduce nitrate leaching in ground and surface water. This response is attributed to mechanisms such as a reduction in water drainage volume, reduction in nitrate concentration in the leachate, and microbial immobilization from C inputs (Quemada et al., 2013; Valkama et al., 2015; Thapa et al., 2018). Improvements in soil aggregation upon adoption of soil health practices may also decrease soil compaction and water saturation (e.g. anaerobic soil conditions), reducing the potential for N losses following intense precipitation or irrigation events. A recent meta-analysis found that continuous living roots in the system with the use of cover crops improve soil structure and enhance water cycling through increased water infiltration rates (Basche and DeLonge, 2019). Thus, the observed improved soil infiltration, organic matter content, water-extractable organic C and N and soil health score in fields with incremental additions of continuous soil cover with the use of cover crop corroborate with findings from previous studies (Table 2.2).

There is growing interest in the U.S. Midwest in the implementation of conservation practices to reduce nutrient losses from farmland and improve fertilizer management of high-input demanding crops such as corn and wheat (García et al., 2016). Because soil biological properties are often overlooked in traditional nutrient recommendations, we analyzed not only data on soil physical, chemical and biological properties, but also the plant-available nutrient and fertilizer rate recommendation portions of the HSHT for sites with incremental changes in cover crop use over time (Figure 2.6). A unique aspect of the HSHT nutrient recommendation, particularly for N, is the subtraction of the plant available N from the expected yield (Yost et al., 2018). This credit accounts not only for the residual inorganic N (nitrate and ammonium), commonly available in traditional soil fertility tests, but also estimates of mineralizable N during a 24-h aerobic incubation, an additional credit, termed organic N release, that traditional fertility tests do not account for.

In our analysis, greater organic nitrogen credits (organic N release) were obtained from fields with higher intensification in CCU, which lowered the requirements for fertilizer inputs for both corn and wheat (Figure 2.6). A recent study evaluating the HSHT for corn N recommendations across eight Midwest states found that the plant-available N portion of the HSHT recommendation accounted for up to 49% of the variation in economically optimum N rate (EONR) and could potentially be used, with other factors, to better estimate EONR for corn in the Midwest (Yost et al., 2018). Similarly, a study including 111 fields adopting minimum tillage, multi-species cover cropping, and amendment with animal manures as soil health practices found a strong association between both HSHT variables, soil-test biological activity, and N mineralization, and corn EONR (Franzluebbers, 2020). Another recent large-scale study using data from multiple N rate trials across central and eastern Corn Belt found that biological indicators of soil health (e.g., permanganate oxidizable C, soil protein, and mineralizable C) accounted for approximately 20% of N fertilizer effects (Wade et al., 2020). Although understanding site-specific effects of cover cropping EONR for corn and wheat needs further experimental work (cover crop decomposition experiments, for example), and HSHT fertilizer recommendations need further testing and calibration which was beyond the scope of our study, our results suggest the importance of accounting for soil biological activity and its association with nutrient credits as indicators of soil health to increase profit and reduce environmental impacts. Taken together, these recent efforts in understating soil biology to fine-tune nutrient fertilizer recommendations along with the results from our study suggest that soil health-promoting practices can provide a greater supply of N which can be used to reduce nutrient fertilizer costs and improve system input use efficiency.

Limitations of the framework and uncertainties

Due to the distribution of sites, farmer-selected management practices and protocol analysis (HSHT) to study, there were some limitations with our data and analytic approach. First, ecological intensification via the use of organic amendment was not well represented in our data – we only considered a 5-year frequency of organic amendment in the cropping system. The quantity and type of organic amendments were also not included because of uncertainties regarding the exact composition or the amount applied. Second, the data is essentially agroecosytem-focused, and extrapolation of our results to natural ecosystems may not be possible. For example, organic matter and infiltration changes might be more difficult to detect in natural ecosystems than in agroecosystems. However, the effect of intensification of soil health related practices on soil properties should be robust regardless of ecosystem types, which share the same soil formation mechanisms. Third, HSHT analytical procedures use unique soil extractants to measure microbial-available C and N pools, which require further data calibration for comparisons to traditional soil test labs. Additionally, the measured C and N pools are constantly replenished and rapidly changed by plant root exudates and dead microbial cells. In this paper, we focused on trends in the comparison of different soil health management systems over absolute values when interpreting HSHT results. Despite these limitations, the novelty in this effort is to account for the often-overlooked role that field management history plays when analyzing data from participatory, on-farm research (Supplementary Table S1). This allowed us to propose a classification framework of ecological intensification that considers multiple soil health management practices.

Conclusions

This study was conducted on working farmlands, allowing us to consider a large variation in soil management decisions and field (e.g. crop sequence and species selection, avoidance of mechanical disturbance, application of organic amendment, elimination of fallow periods, and crop-livestock integration) in the dataset. The intensified cropping systems included in our study are possible alternatives to the conventional farming practices (input-intensive, maize-dominated rotations with limited diversity) in Midwestern U.S. (Figure 2.3). Overall, our results indicate that (i) ecological intensification affected all properties commonly used in soil health assessments, but the sensitivity of the impacts of management varied among the physical, chemical and biological soil properties; (ii) the feature of continuous living cover and roots in the soil was reflected by the variable CCU index – the frequency of cover crop use in the rotation system. Relative importance showed that intensification in CCU was the most important management factor influencing changes in soil properties; and (iii) soil-test hypothetical N credits in cropping systems intensified with cover crop use can reduce nutrient fertility needs substantially as opposed to less intensified systems, in which organic nutrient credits are minimal and may not have an impact on the amount of N fertilizer required. The data presented here demonstrate the importance of understanding how ecologically based intensification of agricultural systems affects soil properties. Reported findings are informative and beneficial for promoting soil health management practices, better-informing farmers about management strategies that foster healthier soils and represent steps forward in land stewardship.

Acknowledgments

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References

Alhameid, A., Ibrahim, M., Kumar, S., Sexton, P., Schumacher, T.E., 2017. Soil organic carbon changes impacted by crop rotational diversity under no-till farming in South Dakota, USA. Soil Sci. Soc. Am. J. 81, 868–877. https://doi.org/10.2136/sssaj2016.04.0121.

Angers, D. A., Eriksen-Hamel, N. S., 2008. Full-inversion tillage and organic carbon distribution in soil profiles: a meta-analysis. Soil Science Society of America Journal, 72(5), 1370-1374. https://doi.org/10.2136/sssaj2007.0342.

Arshad, M. A., Martin, S., 2002. Identifying critical limits for soil quality indicators in agro-ecosystems. Agriculture, Ecosystems & Environment, 88(2), 153-160. https://doi.org/10.1016/S0167-8809(01)00252-3.

Balota, E.L., Colozzi, A., Andrade, D.S., Dick, R.P., 2004. Long-term tillage and crop rotation effects on microbial biomass and C and N mineralization in a Brazilian Oxisol. Soil & Tillage Research, 77, 137–145. https://doi.org/10.1016/j.still.2003.12.003.

Basche, A. D., DeLonge, M. S., 2019. Comparing infiltration rates in soils managed with conventional and alternative farming methods: A meta-analysis. PloS one, 14(9). https://doi.org/10.1371/journal.pone.0215702.

Basche, A. D., Roesch-McNally, G. E., 2017. Research topics to scale up cover crop use: Reflections from innovative Iowa farmers. Journal of Soil and Water Conservation, 72(3), 59A-63A. https://doi.org/10.2489/jswc.72.3.59A.

Baumgart-Getz, A., Prokopy, L. S., Floress, K., 2012. Why farmers adopt best management practice in the United States: A meta-analysis of the adoption literature. Journal of environmental management, 96(1), 17-25. https://doi.org/10.1016/j.jenvman.2011.10.006

Bender, S. F., Wagg, C., van der Heijden, M. G., 2016. An underground revolution: biodiversity and soil ecological engineering for agricultural sustainability. Trends in ecology & evolution, *31*(6), 440-452. https://doi.org/10.1016/j.tree.2016.02.016.

Blake, G., Hartge, K., 1986. Bulk density, in: Klute, A. (Ed.), Methods of soil analysis. Part 1. Physical and mineralogical methods. Madison, WI: ASA and SSSA, pp. 363–375.

Blanco-Canqui, H., Shapiro, C., Jasa, P., Iqbal, J., 2021. No-till and carbon stocks: Is deep soil sampling necessary? Insights from long-term experiments. Soil and Tillage Research, 206, 104840. https://doi.org/10.1016/j.still.2020.104840.

Campbell, C.A., B.G. McConkey, V.O. Biederbeck, R.P. Zentner, D. Curtin, and M.R. Peru., 1998. Long-term effects of tillage and fallow-frequency on soil quality attributes in a clay soil in semiarid southwestern Saskatchewan. Soil Tillage Res. 46:135–144. https://doi.org/10.1016/S0167-1987(98)00027-0.

Caudle D., DiBenedetto, J., Karl, M., Sanchez, H., Talbot, C., 2013. Interagency ecological site handbook for rangelands. US Department of the Interior, Bureau of Land Management. https://jornada.nmsu.edu/sites/jornada.nmsu.edu/files/InteragencyEcolSiteHandbook.pdf (accessed 2 March 2021).

Chahal, I., Van Eerd, L. L., 2018. Evaluation of commercial soil health tests using a medium-term cover crop experiment in a humid, temperate climate. Plant and Soil 427(1-2): 333 351-367. https://doi.org/10.1007/s11104-018-3653-2.

Chevan, A., Sutherland, M., 1991. Hierarchical Partitioning. The American Statistician 45, 90–96. DOI: 10.1080/00031305.1991.10475776.

Church, S. P., Lu, J., Ranjan, P., Reimer, A. P., Prokopy, L. S., 2020. The role of systems thinking in cover crop adoption: Implications for conservation communication. Land Use Policy, 94, 104508. https://doi.org/10.1016/j.landusepol.2020.104508.

Congreves, K.A., Hayes, A., Verhallen, E.A., van Eerd, L.L., 2015. Long-term impact of tillage and crop rotation on soil health at four temperate agroecosystems. Soil Tillage Res. 152, 17–28. https://doi.org/10.1016/j.still.2015.03.012.

de Paul Obade, V., Lal, R., 2016. Towards a standard technique for soil quality assessment. Geoderma, 265, 96-102. https://doi.org/10.1016/j.geoderma.2015.11.023.

DeLonge, M. and Basche, A.D., 2018. Managing grazing lands to improve soils and promote climate change adaptation and mitigation: a global synthesis. Renewable Agriculture and Food Systems, pp 267–278. doi 10.1017/S1742170517000588

Delgado, J. A., Groffman, P. M., Nearing, M. A., Goddard, T., Reicosky, D., Lal, R., Kitchen, N. R., Rice, C. R., & Salon, P. 2011. Conservation practices to mitigate and adapt to climate change. Journal of soil and water conservation, 66(4), 118A-129A. DOI: https://doi.org/10.2489/jswc.66.4.118A.

Duke, S. O., Powles, S. B., 2008. Glyphosate: a once-in-a-century herbicide. Pest Management Science: formerly Pesticide Science, 64(4), 319-325. https://doi.org/10.1002/ps.1518

Evans, D. L., Quinton, J. N., Davies, J. A. C., Zhao, J., Govers, G., 2020. Soil lifespans and how they can be extended by land use and management change. Environmental Research Letters, 15(9), 0940b2.

Ferro, N.D., Charrier, P., Morari, F., 2013. Dual-scale micro-CT assessment of soil structure in a long-term fertilization experiment. Geoderma 204–205, 84–93. https://doi.org/10.1016/j.geoderma.2013.04.012.

Franzen, D.W., 2017. Soil variability and fertility management, in: Shannon, D.K., Clay, D.E., Kitchen, N. (Eds.), Precision agriculture basics. ASA, CSSA, SSSA, Madison, WI.

Franzluebbers, A. J., 2020. Soil-test biological activity with the flush of CO2: V. Validation of nitrogen prediction for corn production. Agronomy Journal, 112(3), 2188-2204. https://doi.org/10.1002/agj2.20094.

Franzluebbers, A., 2021. Assessment and Interpretation of Soil-Test Biological Activity, in: Karlen, D.L., Stott, D. E., Mikha, M. M. (EDs.), Laboratory Methods for Soil Health Analysis, Vol. 2. Madison, WI: SSSA, pp. 126-151.

García, A.M., Alexander, R.B., Arnold, J.G., Norfleet, L., White, M.J., Robertson, D.M., Schwarz, G., 2016. Regional effects of agricultural conservation practices on nutrient transport in the Upper Mississippi River Basin. Environ. Sci. Technol. 50, 6991–7000. https://doi.org/10.1021/acs.est.5b03543.

Gardner, J.B., Drinkwater, L.E., 2009. The fate of nitrogen in grain cropping systems: a meta-analysis of 15N field experiments. Ecol. Appl. 19, 2167–2184. https://doi.org/10.1890/08-1122.1

Gardner,W. H., 1986. Water content, in A. Klute (Ed.), Methods of soil analysis. Part 1. Physical and mineralogical methods. Madison, WI: SSSA and ASA, pp. 493–544.

Givens, W. A., Shaw, D. R., Kruger, G. R., Johnson, W. G., Weller, S. C., Young, B. G., ... & Jordan, D., 2009. Survey of tillage trends following the adoption of glyphosate-resistant crops. Weed technology, 23(1), 150-155. https://doi.org/10.1614/WT-08-038.1

Gliessman, S., 2014. Agroecology: The Ecology of Sustainable Food Systems, 3rd ed. Taylor & Francis Group, Boca Raton.

Govaerts, B., Sayre, K. D., Deckers, J., 2006. A minimum data set for soil quality assessment of wheat and maize cropping in the highlands of Mexico. Soil and Tillage Research, 87(2), 163-174. https://doi.org/10.1016/j.still.2005.03.005.

Grömping, U., Lehrkamp, M., 2015. Package 'relaimpo': Relative importance of regressors in linear models. https://cran.r-project.org/web/packages/relaimpo/ (accessed 2 March 2021).

Guo, Y., Fan, R., Zhang, X., Zhang, Y., Wu, D., McLaughlin, N., ... Liang, A., 2020. Tillage-induced effects on SOC through changes in aggregate stability and soil pore structure. Science of the Total Environment, 703, 134617. https://doi.org/10.1016/j.scitotenv.2019.134617.

Haney interpretation guide. Wards Laboratories. https://www.wardlab.com/wp-content/uploads/2020/02/Haney-Rev-1.0-Interpretation-Guide-PDF-1.pdf (accessed 2 March 2021).

Haney, R.L., Haney, E.B., Hossner, L.R., Arnold, J.G., 2006. Development of a new soil Extractant for simultaneous phosphorus, ammonium, and nitrate analysis. Commun. Soil Sci. Plant Anal. 37(11–12):1511–1523. https://doi.org/10.1080/00103620600709977.

Haney, R.L., Haney, E.B., Hossner, L.R., Arnold, J.G., 2010. Modifications to the new soil extractant H3A-1: A multinutrient extractant. Commun. Soil Sci. Plant Anal. 41(12):1513–1523. https://doi.org/10.1080/00103624.2010.482173.

Hart, C.E., Hayes, D. J., Jacobs, K. L., Schulz, L. L., Crespi, J. M., 2020. The Impact of COVID-19 on Iowa's Corn, Soybean, Ethanol, Pork, and Beef Sectors. Center for Agricultural and Rural Development, Iowa State University. CARD Policy Brief 20-PB 28. https://www.card.iastate.edu/products/publications/pdf/20pb28.pdf (accessed 2 March 2021).

Hermle, S., Anken, T., Leifeld, J., Weisskopf, P., 2008. The effect of the tillage system on soil organic carbon content under moist, cold-temperate conditions. Soil & Tillage Research, 98, 94–105. https://doi.org/10.1016/j.still.2007.10.010.

Hiller, T.L.; Powell, L.A.; McCoy, T.D.; Lusk, J.J., 2009. Long-Term Agricultural Land-Use Trends in Nebraska, 1866–2007. Great Plains Res. 19, 225–237.

Jiao, Y., Whalen, J.K., Hendershot, W.H., 2006. No-tillage and manure applications increase aggregation and improve nutrient retention in a sandy-loam soil. Geoderma 134, 24–33. https://doi.org/10.1016/j.geoderma.2005.08.012.

Kaiser, M., Piegholdt, C., Andruschkewitsch, R., Linsler, D., Koch, H. J., Ludwig, B., 2014. Impact of tillage intensity on carbon and nitrogen pools in surface and sub-surface soils of three long-term field experiments. European journal of soil science, 65(4), 499-509. https://doi.org/10.1111/ejss.12146.

Karlen, D. L., Veum, K. S., Sudduth, K. A., Obrycki, J. F., Nunes, M. R., 2019. Soil health assessment: Past accomplishments, current activities, and future opportunities. Soil and Tillage Research, 195, 104365. https://doi.org/10.1016/j.still.2019.104365.

Kay, B.D., Vanden Bygaart, A.J., 2002. Conservation tillage and depth stratification of porosity and soil organic matter. Soil Till. Res. 66, 107–118. https://doi.org/10.1016/S0167-1987(02)00019-3.

Knowler, D., Bradshaw, B. 2007. Farmers' adoption of conservation agriculture: A review and synthesis of recent research. Food policy, 32(1), 25-48. https://doi.org/10.1016/j.foodpol.2006.01.003

Krupek, F.S., Basche, A., Redfearn, D., Thompson, L., 2019a. Farmers Find Solutions Through Nebraska Soil Health Initiative. CropWatch article. https://cropwatch.unl.edu/2019/farmers-find-solutions-through-nebraska-soil-health-initiative (accessed 2 March 2021).

Krupek, F.S., Basche, A., Redfearn, D., Thompson, L., 2019b. Why Growers are Adopting Practices to Build Soil Health. CropWatch article. https://cropwatch.unl.edu/2019/farmers-on-soil-health-practices (accessed 2 March 2021).

Lal, R., 2013. Climate-strategic agriculture and the water-soil-waste nexus. Journal of Plant Nutrition and Soil Science, 176(4), 479-493. https://doi.org/10.1002/jpln.201300189.

Li, Y., Li, Z., Cui, S., Jagadamma, S., Zhang, Q., 2019. Residue retention and minimum tillage improve physical environment of the soil in croplands: A global meta-analysis. Soil and Tillage Research, 194, 104292. https://doi.org/10.1016/j.still.2019.06.009.

MacLaren, C., Storkey, J., Strauss, J., Swanepoel, P., Dehnen-Schmutz, K., 2019. Livestock in diverse cropping systems improve weed management and sustain yields whilst reducing inputs. Journal of applied ecology, 56(1), 144-156. https://doi.org/10.1111/1365-2664.13239.

McDaniel, M. D., Grandy, A. S., Tiemann, L. K., Weintraub, M. N., 2014a. Crop rotation complexity regulates the decomposition of high and low quality residues. Soil Biology and Biochemistry, 78, 243-254. https://doi.org/10.1016/j.soilbio.2014.07.027.

McDaniel, M. D., Tiemann, L. K., Grandy, A. S., 2014b. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecological Applications, 24(3), 560-570. https://doi.org/10.1890/13-0616.1.

Mikha, M.M., Rice, C.W., 2004. Tillage and manure effects on soil and aggregate-associated carbon and nitrogen. Soil Science Society of America Journal, 68, 809–816. https://doi.org/10.2136/sssaj2004.8090.

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.

Nelson, D.W., Sommers, L.E., 1996. In: Sparks, D.L. (Ed.), Methods of Soil Analysis. Part 3, SSSA Book Series, Madison, pp. 961–1010.

NOAA National Centers for Environmental Information (NCEI), 2020a. State of the Climate: National Climate Report for 2019. https://www.ncdc.noaa.gov/sotc/national/201913/supplemental/page-1 (accessed 26 January 2020).

NOAA National Centers for Environmental Information (NCEI), 2020b. U.S. Billion-Dollar Weather and Climate Disasters. https://www.ncdc.noaa.gov/billions/ (accessed 26 January 2020).

NRCS-USDA, 2011. Planting Specification Guide: Cover Crop NH-340. U.S. Department of Agriculture Natural Resources Conservation Service. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1081555.pdf (accessed 19 January 2021).

Nunes, M.R., van Es, H.M., Schindelbeck, R., Ristow, A.J., Ryan, M., 2018. No-till and cropping system diversification improve soil health and crop yield. Geoderma 328, 30–43. https://doi.org/10.1016/j.geoderma.2018.04.031.

Oliveira, M. C., Butts, L., Werle, R., 2019. Assessment of cover crop management strategies in Nebraska, US. Agriculture, 9(6), 124. https://doi.org/10.3390/agriculture9060124

Parra, B. J., Becker, A. R., Cantú, M. P., 2011. Condición física de suelos en diferentes sistemas de manejo agrícolas del centro sur de Córdoba. Ciencia del suelo, 29(2), 241-251.

Pires, L. F., Borges, J. A., Rosa, J. A., Cooper, M., Heck, R. J., Passoni, S., Roque, W. L., 2017. Soil structure changes induced by tillage systems. Soil and Tillage Research, 165, 66-79. https://doi.org/10.1016/j.still.2016.07.010.

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

Prokopy, L. S., Gramig, B. M., Bower, A., Church, S. P., Ellison, B., Gassman, P. W., ... Ulrich-Schad, J. D., 2020. The urgency of transforming the Midwestern US landscape into more than corn and soybean. Agric Hum Value, 37, 537-539. https://doi.org/10.1007/s10460-020-10077-x.

Quemada, M., Baranski, M., Nobel-de Lange, M. N. J., Vallejo, A., Cooper, J. M., 2013. Meta-analysis of strategies to control nitrate leaching in irrigated agricultural systems and their effects on crop yield. Agriculture, ecosystems & environment, 174, 1-10. https://doi.org/10.1016/j.agee.2013.04.018.

R Core Team, 2018. R: A language and environment for statistical computing. https://www.R-project.org/ (accessed 2 March 2021).

Rakkar, M. K., Blanco-Canqui, H., 2018. Grazing of crop residues: Impacts on soils and crop production. Agriculture, Ecosystems & Environment, 258, 71-90. https://doi.org/10.1016/j.agee.2017.11.018.

Reynolds, W. D., Bowman, B. T., Drury, C. F., Tan, C. S., Lu, X., 2002. Indicators of good soil physical quality: density and storage parameters. Geoderma, 110(1-2), 131-146. https://doi.org/10.1016/S0016-7061(02)00228-8.

Rhymes, J. M., Wynne-Jones, S., Williams, A. P., Harris, I. M., Rose, D., Chadwick, D. R., & Jones, D. L., 2021. Identifying barriers to routine soil testing within beef and sheep farming systems. Geoderma, 404, 115298. https://doi.org/10.1016/j.geoderma.2021.115298

Rojas, J. M., Prause, J., Sanzano, G. A., Arce, O. E. A., Sánchez, M. C., 2016. Soil quality indicators selection by mixed models and multivariate techniques in deforested areas for agricultural use in NW of Chaco, Argentina. Soil and Tillage Research, 155, 250-262. https://doi.org/10.1016/j.still.2015.08.010.

Roper, W. R., Osmond, D. L., Heitman, J. L., Wagger, M. G., Reberg-Horton, S. C., 2017. Soil health indicators do not differentiate among agronomic management systems in North Carolina soils. Soil Science Society of America Journal, 81(4), 828-843. https://doi.org/10.2136/sssaj2016.12.0400er.

Sanzano, G. A., Corbella, R. D., García, J. R., Fadda, G. S., 2005. Degradación física y química de un Haplustol típico bajo distintos sistemas de manejo de suelo. Ciencia del suelo, 23(1), 93-100.

Seifert, C. A., Azzari, G., Lobell, D. B., 2018. Satellite detection of cover crops and their effects on crop yield in the Midwestern United States. Environ. Res. Lett. 13, 064033.

Sherwood, S., Uphoff, N., 2000. Soil health: research, practice and policy for a more regenerative agriculture. Applied Soil Ecology, 15(1), 85-97. https://doi.org/10.1016/S0929-1393(00)00074-3.

Smith, R.E., 1999. Technical note: Rapid measurement of soil sorptivity. Soil Sci. Soc. Am. J. 63: 55– 57. https://doi.org/10.2136/sssaj1999.03615995006300010009x.

Soil Health Institute, 2018. Conference on the Connections Between Soil Health and Human Health. https://soilhealthinstitute.org/wp-content/uploads/2019/03/SH-HH-post-conference-report-Final-030519.pdf (accessed 24 March 2020).

Soil Survey Staff, 1999. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. 2nd edition. Natural Resources Conservation Service. U.S. Department of Agriculture Handbook 436.

Stewart, R. D., Jian, J., Gyawali, A. J., Thomason, W. E., Badgley, B. D., Reiter, M. S., Strickland, M. S., 2018. What we talk about when we talk about soil health. Agricultural & Environmental Letters, 3(1). https://doi.org/10.2134/ael2018.06.0033.

Taylor, S. D., He, Y., Hiscock, K. M., 2016. Modelling the impacts of agricultural management practices on river water quality in Eastern England. Journal of Environmental Management, 180, 147-163. https://doi.org/10.1016/j.jenvman.2016.05.002.

Thapa, R., Mirsky, S. B., Tully, K. L., 2018. Cover crops reduce nitrate leaching in agroecosystems: A global meta-analysis. Journal of environmental quality, 47(6), 1400-1411. https://doi.org/10.2134/jeq2018.03.0107.

Thompson, L. J., Glewen, K. L., Elmore, R. W., Rees, J., Pokal, S., Hitt, B. D., 2019. Farmers as Researchers: In-depth Interviews to Discern Participant Motivation and

Impact. Agronomy Journal, 111(6), 2670-2680. https://doi.org/10.2134/agronj2018.09.0626.

Tiemann, L.K., Grandy, A.S., Atkinson, E.E., Marin-Spiotta, E., McDaniel, M.D., 2015. Crop rotational diversity enhances belowground communities and functions in an agroecosystem. Ecol. Lett. 18, 761–771. https://doi.org/10.1111/ele.12453.

USDA-NASS, 2019. 2017 Census of Agriculture, Summary and State Data. U.S. Department of Agriculture National Agricultural Statistics Service. https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf (accessed 19 February 2021).

USDA-NRCS, 1981. Land resource regions and major land resource areas of the United States (USDA Handbook 296). Washington, DC: U.S. Government Printing Office.

USDA–NRCS, 2018. Soil health. U.S. Department of Agriculture Natural Resources Conservation Service. https://www.nrcs.usda.gov/wps/portal/ nrcs/main/soils/health/ (accessed 4 May 2020).

USDA-NRCS, 2020. Soil health technical note No. 450-06. Cropland in-field soil health assessment guide. U.S. Department of Agriculture Natural Resources Conservation Service. https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/assessment/ (accessed 19 February 2021).

Valkama, E., Lemola, R., Känkänen, H., Turtola, E., 2015. Meta-analysis of the effects of undersown catch crops on nitrogen leaching loss and grain yields in the Nordic countries. Agriculture, Ecosystems & Environment, 203, 93-101. https://doi.org/10.1016/j.agee.2015.01.023.

Villamil, M. B., Miguez, F. E., Bollero, G. A., 2008. Multivariate analysis and visualization of soil quality data for no-till systems. Journal of environmental quality, 37(6), 2063-2069. https://doi.org/10.2134/jeq2007.0349.

Wade, J., Culman, S. W., Logan, J. A., Poffenbarger, H., Demyan, M. S., Grove, J. H., ... West, J. R., 2020. Improved soil biological health increases corn grain yield in N fertilized systems across the Corn Belt. Scientific reports, 10(1), 1-9. https://doi.org/10.1038/s41598-020-60987-3.

Westhoff, P., Meyer, S., Binfield, J., Gerlt, S., 2020. Early Estimates of the Impacts of COVID-19 on U.S. Agricultural Commodity Markets, Farm Income and Government Outlays. Food and Agricultural Policy Research Institute, University of Missouri. FAPRI-MU

Report #02–20. https://www.agri-pulse.com/ext/resources/pdfs/FAPRI-Report-02-20.pdf (accessed 2 March 2021).

Whalen, J.K., Hu, Q., Liu, A., 2003. Compost applications increase water-stable aggregates in conventional and no-tillage systems. Soil Sci. Soc. Am. J. 67, 1842–1847. https://doi.org/10.2136/sssaj2003.1842.

Williams, H., Colombi, T., Keller, T., 2020. The influence of soil management on soil health: An on-farm study in southern Sweden. Geoderma, 360, 114010. https://doi.org/10.1016/j.geoderma.2019.114010.

Wortmann, C.S., Shapiro, C.A., 2008. The effects of manure application on soil aggregation. Nutr. Cycl. Agroecosyst. 80, 173–180. https://doi.org/10.1007/s10705-007-9130-6.

Xue, R., Wang, C., Liu, M., Zhang, D., Li, K., Li, N., 2019. A new method for soil health assessment based on Analytic Hierarchy Process and meta-analysis. Science of The Total Environment, 650, 2771-2777. https://doi.org/10.1016/j.scitotenv.2018.10.049.

Yost, M. A., Veum, K. S., Kitchen, N. R., Sawyer, J. E., Camberato, J. J., Carter, P. R., ... Nafziger, E. D., 2018. Evaluation of the Haney Soil Health Tool for corn nitrogen recommendations across eight Midwest states. Journal of Soil and Water Conservation, 73(5), 587-592. https://doi.org/10.2489/jswc.73.5.587.

Zuber, S. M., Kladivko, E., 2018. How to understand and interpret soil health tests. Purdue Extension. https://www.extension.purdue.edu/extmedia/ay/ay-366-w.pdf (accessed 19 January 2021).

Zuber, S. M., Behnke, G. D., Nafziger, E. D., Villamil, M. B., 2017. Multivariate assessment of soil quality indicators for crop rotation and tillage in Illinois. Soil and Tillage Research, 174, 147-155. https://doi.org/10.1016/j.still.2017.07.007.

CHAPTER 3 : ASSESSING HOW COVER CROPS CLOSE THE SOIL HEALTH GAP IN ON-FARM EXPERIMENTS

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Abstract

Assessing cover crop (CC) success as a soil health-promoting practice at the farm scale remains a challenge. At four on-farm CC experiments in Nebraska, we quantified soil health relative to a reference soil. We examined physical, chemical, and biological properties in near-surface soil. CCs reduced the soil health gap between bare (no-CC) and reference soil in the short (3 yrs.) timescale, but magnitude of responses depended on cropland management history and ecological dynamics of plant communities of reference sites. Increases in soil health relative to reference soils showed some relationship to increases in soybean (*Glycine max* (L.) Merr) and corn (*Zea mays* L.) yields. Clear discrimination of reference from bare soils was most influenced by organic matter and infiltration measurements conducted under the highest sampling intensity. Framing soil metrics relative to reference soils and ensuring appropriate sampling intensity are important to quantify CC impacts on farm landscapes.

Introduction

Cover crops (CC) are promoted as a strategy for changing soil properties that lead to improved soil function such as water infiltration, carbon sequestration, nutrient retention, erosion control, and belowground biodiversity. Examples from long-term research (Mbuthia et al., 2015; DeLaune et al., 2019), literature synthesis (Schipanski et al., 2014; Blanco-Canqui et al., 2015) and on-farm trials (Welch et al., 2016; Wood and Bowman, 2021) have documented soil property improvements (e.g., organic matter, water infiltration, β-glucosidase activity, aggregation) with CCs. Yet it remains difficult to detect CC-related changes on soil, particularly in on-farm studies where large experimental plots include greater inherent variability. In this analysis, we incorporated two approaches to refine the assessment of CC impacts on soil properties: reference soils and sampling intensity strategies.

Soil property changes relative to reference soils have been applied to understand realistically attainable improvements resulting from management changes (Dobarco et al., 2021; Maharjan and Das, 2021). The concept of reference state was first introduced in ecological site to understand rangeland health (Caudle et al., 2013; Pellant et al., 2005) and represents undisturbed soils with a minimum degree of anthropogenic modification (Dobarco et al., 2021). Advancements on the concept of reference state are being applied in dynamic soil properties (Wills et al., 2017), temporal evolution of soil properties for thresholds and stages of degradation (Kuzyakov and Zamanian, 2019), mapping soil classes and land use for reference state identification (Dobarco et al., 2021; Maharjan and Das, 2021), and the soil health gap concept (Maharjan et al., 2020). However, much less is known about the application of reference soils on on-farm assessments of soil changes with CCs.

Assessing changes in soil properties with CCs at the farm scale is potentially also influenced by sampling strategy. In a meta-analysis of 86 studies in North America, Stewart et al. (2018) found that water infiltration had high responsiveness to 1-3 years of CCs adoption, being a key parameter to compare cropland soil health to reference soils. Similar to other properties, water infiltration is predominantly dependent on the spatial and temporal scale of assessment (de Lima Moraes et al., 2020). As a result, spatial and temporal replication of measurements is usually required for adequate soil hydrologic characterization (Reynolds et al., 2002).

In this study, we quantified soil property changes relative to reference soils in on-farm CC trials. Specific objectives were (1) to apply the concept and assess whether soil health gap relative to reference soils has significant relationship with crop yield and (2) to understand soil property combinations and sampling strategies that maximally distinguish soils with a perenniality gradient (reference, CC and no-CC).

Materials and Methods

On-farm experiments

Four on-farm trials were part of the Nebraska Soil Health Initiative between 2016 and 2021. Soils were classified predominantly as Mollisols, Entisols and Alfisols (Krupek et al., 2022), with slope gradients ranging from 1-23% (Soil Survey Staff, 1999). Trials were randomized complete block designs with treatments of multispecies CC and no-CC across approximately 30-hectare fields located in Greeley, Howard, Merrick and Colfax counties. In a corn-soybean rotation, farmers introduced diverse CC mixtures of cool-season small grain cereals, legumes, brassicas, and warm-season summer annual grasses based on NRCS CC guidelines (Nebraska Extension On-Farm Research, 2021; USDA-NRCS, 2011). Trials required farmer-reported grain yield data collected using a test plot weigh wagon (Greeley) or combine with a calibrated yield monitor (Howard, Merrick and Colfax).

Soil sampling

Samples were collected in July 2019, three years after the implementation of the first CC treatment, when plots were around soybean growth stage R6. We sampled 0-5 cm depth soils using a 32-mm core diameter sampler. Minimally disturbed soils (i.e., sites representing perennial grassland or less disturbed land uses) from nearby (<5 km) farmland were collected to determine soil health benchmarks (Maharjan et al., 2020). Selection of reference sites accounted for soil and climate variabilities within on-farm trials. Each reference site had functional Ecological Site Description vegetation with major components of the historical climax plant community. Based on state and transition models (Bestelmeyer et al., 2017), field assessments showed vegetation communities in “Native/Invaded Grass State 2.1”, “Switchgrass/Prairie Sand Reed Plant

Community 1.2", "Native/Invaded Mix State Community 2.2 – Codominant", and "Native/Invaded Grass State 2.1" for reference soils in Greeley, Merrick, Colfax, and Howard respectively.

To minimize spatial soil variation, in each sample point 10 cores were collected around a 6×24-m sample area, composited, and shipped on ice to Ward Laboratories (Kearney, Nebraska). Soil property analysis were conducted using standard methods for soil organic matter (Nelson and Sommers, 1996), nitrate-nitrogen (Keeney and Nelson, 1982), β-glucosidase activity (Tabatabai, 1994), exchangeable bases (Thomas, 1982), and total elemental iron and manganese. One intact soil core was collected per sample area to determine bulk density by the core method (Blake and Hartge, 1986). Wet aggregate stability, expressed as mean weight diameter (MWD) of water-stable aggregates, was measured by wet sieving method (Nimmo and Perkins, 2002) using a modified Yoder wet-sieving device (Yoder, 1936) from the University of Nebraska-Lincoln.

Multiple measurements of initial water infiltration (Smith et al., 1999) were conducted in 2019 and 2021 to assess sampling intensity strategies that maximally distinguish soil managements. In the 6×24-m sample area, we performed two (N=2), three (N=3), four (N=4), and five (N=5) consecutive measurements of water infiltration (Figure 3.1A), representing a gradual increase in sampling intensity.

Data analysis

To describe cropland soil function compared to its local native potential, we calculated a relative soil health index (RSH) as suggested by Williams et al. (2020). For each on-farm site (i) soil property values for the CC and no-CC (f) were divided by the respective value for the reference soil (r).

$$RSH = \frac{Soil\ property\ value_{if}}{Soil\ property\ value_{ir}} \tag{1}$$

RSH concept was applied to properties that follow “more is better” and “less is better” patterns according to scoring functions of the Cornell comprehensive assessment of soil health (Moebius et al. 2007). Higher infiltration, aggregate stability, β-glucosidase, organic matter, nitrate, and CEC values relative to reference soils indicated improved soil functioning as far as efficient filtration, erosion control, belowground biodiversity, carbon sequestration, and nutrient retention. Likewise, lower values of bulk density, manganese, and iron relative to reference soils were associated with better soil functioning as far as reduced soil compaction and risks associated with micronutrient toxicity.

Yield data were post-processed using Yield Editor (USDA-ARS, 2021) and adjusted to 13% (soybean) and 15.5% (maize) moisture content. Yield data were co-localized from soil sample area (average of 20-30 data points from yield monitoring systems) for Colfax, Howard, and Merrick sites and averaged across strips for Greeley site.

We fit an analysis of variance model for RSH with block and treatment as fixed effects using aov function in R version 4.0.4 (R Core Team, 2020). Mean separation comparisons were performed using lsmeans package at a p-value of 0.10 (Lenth, 2016). We conducted simple linear regressions in lme4 package to understand the relationship between RSH and yield (Bates et al., 2015). Canonical Discriminant Analysis (CDA) was performed using candisc package (Friendly, 2007) to provide insights into appropriate sampling strategy and associations among soil properties to better differentiate management groups.

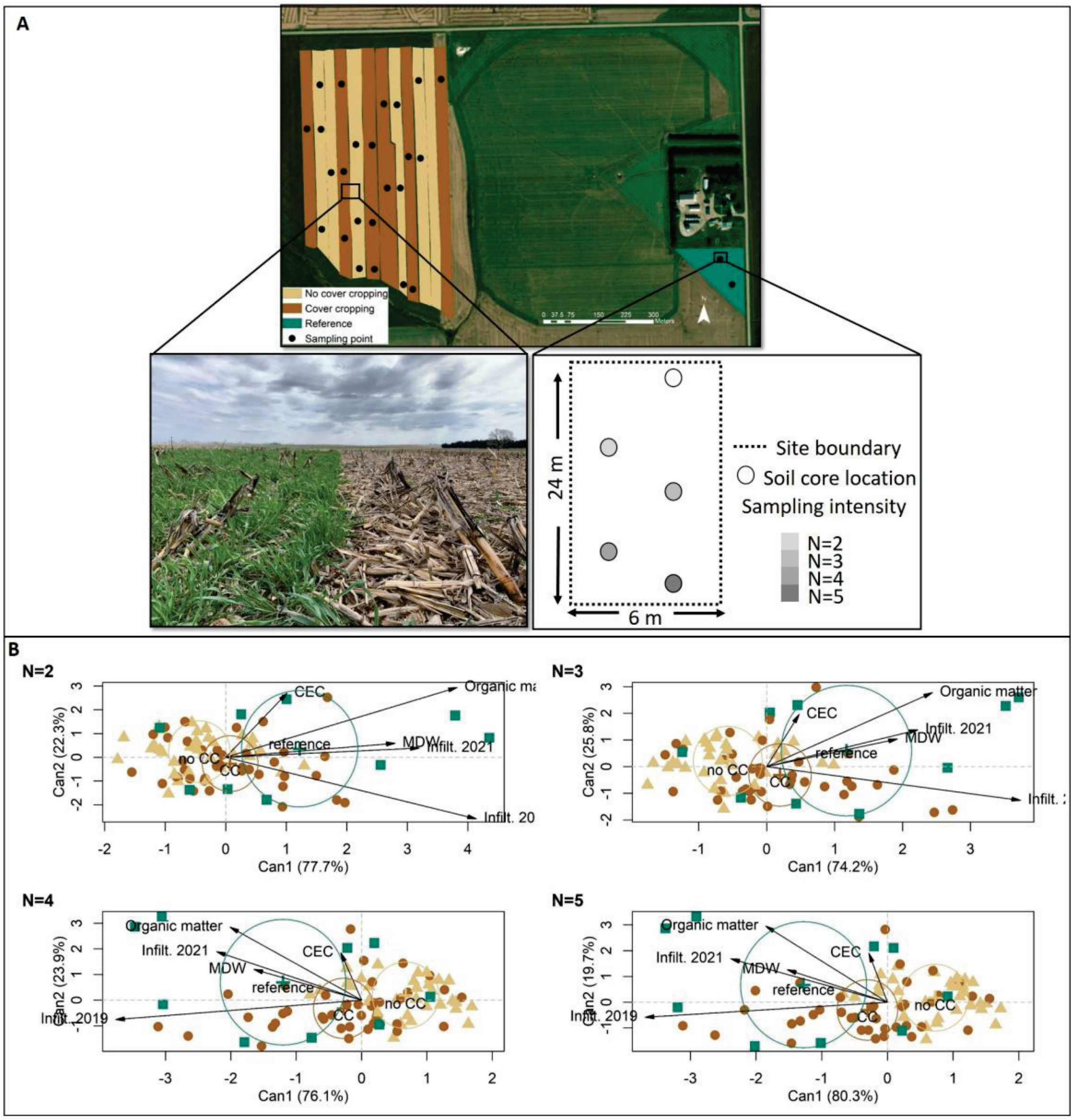

Figure 3.1 (A) Layout of the area within each sampling point for field measurement and multiple soil initial water infiltration measurements of increased sampling intensity (two (N=2), three (N=3), four (N=4), and five (N=5) consecutive measurements of water infiltration). (B) Canonical discriminant analysis of initial water infiltration measurements, CEC, MDW, and organic matter of reference, cover cropping and no cover cropping with increasing sampling intensity. Average of N=2; N= 3; N=4; and N= 5 consecutive measurements of water infiltration per sampling location. The scores along the first two axes are shown. Reference, cover cropping and no cover cropping are indicated with different symbols (square, circle, and triangle, respectively). Field clusters are indicated by ovals with dots representing the group centroid for each treatment in a 95% confidence ellipse. Differences between treatments (represented by distance between ellipses) increase with greater sampling intensity.

Results and Discussion

Reference state comparisons determine how CCs close the soil health gap

For “more is better” properties, CCs had higher cumulative RSH values at two sites, and at least one property with a higher RSH value at the other two sites (Figure 3.2A). We observed differences in the magnitude of responses; CCs reduced the soil health gap by 55%, 28%, 17% and 14% in Greeley, Colfax, Howard and Merrick sites, respectively (Figure 3.2A). For “less is better” properties, CC had lower RSH values than no-CC in three out of the four sites, reducing the soil health gap by 67%, 47%, 12% in Colfax, Howard, and Greeley sites, respectively (Figure 3.2B). Across sites and soil properties, Colfax had the greatest magnitude and significant responses to CCs (Figures 3.2A, 3.2B), most likely due to finer texture leading to soil improvements through formation of water-stable aggregates and organic carbon accumulation (Tisdall and Oades, 1982). Most of the soil properties dynamically responded to CC, but responses were site-specific as might be expected for soils from different ecological sites varying in management and vegetation (Figures 3.2A, 3.2B) (Wills et al., 2017). Overall, the RSH concept successfully captured soil function improvements through infiltration, aggregation, erosion control, belowground biodiversity, carbon sequestration, and nutrient retention, all of which were soil concerns identified by our farmers and reasons for experimentation with CC practices as early adopters (Bowman et al., 2022).

RSH concept can illustrate CC impacts and account for soil and climate variabilities. However, cropland management history and state of reference soils, constructed through state and transition models, should be considered (Wills et al., 2017). The highest RSH (“more is better” properties) at Howard and Greeley sites with CCs (Figure 3.2A) is likely results of i) greater CC biomass accumulation than expected for Nebraska agroecosystems (Ruis et al., 2020) at Howard site (3.07 Mg ha-1), ii) long-term (>10 years) no-tillage in Greeley site improving soil environment (Six et al., 2004; Helgason et. al., 2010; Jiang et al., 2011), and iii) comparable vegetation ecological dynamics of reference soils in Greeley and Howard sites (Native/Invaded Grass State 2.1) (Bestelmeyer et al. 2003; Stringham et al. 2003). Such interpretations can serve as a useful tool for soil resources management, bringing the whole ecosystem insight into management decisions.

In six of eight site-experiment years, farmers achieved higher yields when the cropland RSH value for infiltration rate was higher (Figures 3.2C and D). Even though the relationship was positive in most site-experiment years, overall the relationship of grain yield was only weakly associated with RSH and similar to those recently reported for soil health and grain quality (Adhikari et al., 2022). Chalise et al. (2018) similarly found that CC led to increases in soil water infiltration and soybean yield by 80% and 14%, respectively, compared to no-CC. Even though the interpretation of yield and soil health relationships are soil property- and location-specific, several studies suggest that CC adoption can improve the soil fertility, structure, and hydrothermal properties while increasing cash crop yield stability (Crookston et al., 2021; Fontana et al., 2021; Williams et al., 2018). Although the relationship was not more definitive in our analysis, linking soil health relative to a reference state with yield outcomes is an active area of research that deserves more attention in the development of soil health assessments on farms (Wood and Blankinship, 2022).

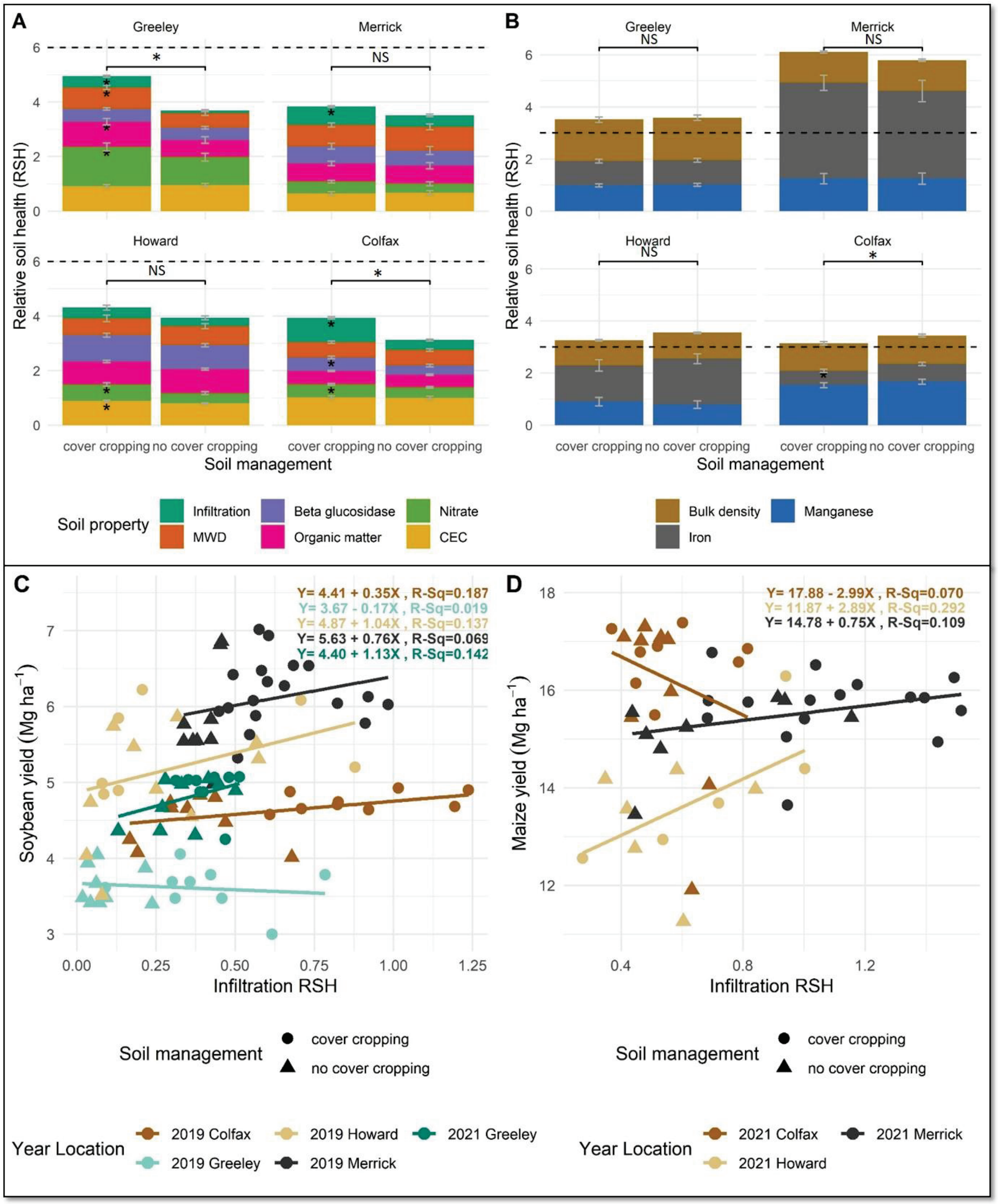

Figure 3.2 Effect of soil management (cover cropping and no cover cropping) on the different components of the relative soil health index for Greeley, Merrick, Howard, and Colfax sites. The horizontal line represents the level of the reference soil, with RSH=6 for "more is better" (A) and RSH=3 for "less is better" (B) properties. Asterisks symbolize significantly different results in CC vs. no-CC comparisons in each field at $p < 0.10$. Abbreviations: MWD=mean weight diameter of water-stable aggregates, CEC=cation exchange

capacity. Simple linear regression models of infiltration RSH and soybean (C) and maize (D) yields. The graphs show the relationship between the measured infiltration RSH values (x) and the estimated yield data (y) using the regression model $y=a\times RSH+b$, where RSH is the infiltration RSH (Eq. (1)). Average coefficients for the predictors as well as R^2, i.e., the variance explained by the regression model, is shown.

The importance of sampling intensity when assessing soil health gap with CC

There was a clear separation between reference vs no-CC and CC vs no-CC in Can1 axis under the highest (N=5) sampling intensity (Figure 3.1B), indicating that five consecutive measurements of water infiltration captured the salient differences among management. Sampling intensity influences the field measurement representativeness and quality of soil dataset quality (Hartemink et al., 2008), which is relevant in sampling methods for digital soil mapping (Guo et al., 2018) and ecosystem restoration of degraded land (Chacoff et al., 2012). The larger influence (greater arrows) of organic matter and water infiltration in separating management groups (Figure 3.1B) is likely the result of improved aggregation (Stumpf et al., 2016), greater fine root production (Sprunger et al., 2017), and enhanced microbial activity (Tiemann & Grandy, 2015) of reference soils representing greater perenniality (Sprunger et al., 2020).

Soil health indicators should be relevant, sensitive, and practical (Lehmann et al., 2020). As a measurement conducted cheaply and with a short turnaround time, water infiltration showed the highest responsiveness to CC across all sites (Figure 3.2A) as reported previously in the literature (Stewart et al., 2018, Basche and DeLonge, 2019; Alvarez et al., 2017). In our study, water infiltration was repeated over space (increased sampling intensity) and time, whereas lab analysis samples were composited from cores collected within each sampling area. Even though collection of multiple samples (e.g., high resolution stratified sampling) for lab analysis could have improved ability in detecting soil property changes (Pennock et al., 2008), these results point to the high variability produced by field and laboratory assessments. This limits researcher's ability to detect statistical significant effects of CC, even when improvements in soil properties or plant productivity are observed by farmers (Gutknecht et al., 2022; Smith, 2020). Together, these results suggest that positive impacts from CC adoption on farms can be achieved by integrating a reference-based soil health concept and adequate sampling.

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References

Adhikari, K., Smith, D. R., Hajda, C., & Owens, P. R. (2022). Can soil health explain grain quality? A case study of a corn field in Texas. *Agricultural & Environmental Letters*, *7*(1), e20078.

Alvarez, R., Steinbach, H. S., & De Paepe, J. L. (2017). Cover crop effects on soils and subsequent crops in the pampas: A meta-analysis. *Soil and Tillage Research*, *170*, 53-65. https://doi.org/10.1016/j.still.2017.03.005

Basche, A. D., & DeLonge, M. S. (2019). Comparing infiltration rates in soils managed with conventional and alternative farming methods: A meta-analysis. *PLoS One*, *14*(9), e0215702. https://doi.org/10.1371/journal.pone.0215702

Bates, D., Maechler, M., Bolker, B., Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, 67(1), 1-48. 10.18637/jss.v067.i01

Bestelmeyer, B. T., Brown, J. R., Havstad, K. M., Alexander, R., Chavez, G., & Herrick, J. E. (2003). Development and use of state-and-transition models for rangelands. *Rangeland Ecology & Management/Journal of Range Management Archives*, *56*(2), 114-126.

Bestelmeyer, B. T., Ash, A., Brown, J. R., Densambuu, B., Fernández-Giménez, M., Johanson, J., ... & Shaver, P. (2017). State and transition models: theory, applications, and challenges. *Rangeland systems*, 303-345.

Blanco-Canqui, H., Shaver, T. M., Lindquist, J. L., Shapiro, C. A., Elmore, R. W., Francis, C. A., & Hergert, G. W. (2015). Cover crops and ecosystem services: Insights from studies in temperate soils. *Agronomy journal*, *107*(6), 2449-2474. https://doi.org/10.2134/agronj15.0086

Blake, G.R., and K.H. Hartge. 1986. Bulk density. Methods of soil analysis. Part 1. SSSA Book Ser. 5. SSSA, Madison, WI. p. 363-375.

Bowman, M., Poley, K., & McFarland, E. (2022). Farmers employ diverse cover crop management strategies to meet soil health goals. *Agricultural & Environmental Letters*, *7*(1), e20070.

Caudle, D., DiBenedetto, J., Karl, M., Sanchez, H., Talbot, C. (2013) Interagency ecological site handbook for rangelands. US Department of the Interior, Bureau of Land Management. https://jornada.nmsu.edu/sites/jornada.nmsu.edu/files/InteragencyEcolSiteHandbook.pdf

Chacoff, N. P., Vázquez, D. P., Lomáscolo, S. B., Stevani, E. L., Dorado, J., & Padrón, B. (2012). Evaluating sampling completeness in a desert plant–pollinator network. *Journal of Animal Ecology*, *81*(1), 190-200. https://doi.org/10.1111/j.1365-2656.2011.01883.x

Chalise, K. S., Singh, S., Wegner, B. R., Kumar, S., Pérez-Gutiérrez, J. D., Osborne, S. L., ... & Rohila, J. S. (2018). Cover crops and returning residue impact on soil organic carbon, bulk density, penetration resistance, water retention, infiltration, and soybean yield. *Agronomy Journal*. 110:99–108. https://doi.org/10.2134/agronj2018.03.0213

Crookston, B., Yost, M., Bowman, M., & Veum, K. (2021). Relationships of on-farm soil health scores with corn and soybean yield in the midwestern United States. *Soil Science Society of America Journal*. https://doi.org/10.1002/saj2.20355

de Lima Moraes, A. G., de Carvalho, D. F., Antunes, M. A. H., Ceddia, M. B., & Flanagan, D. C. (2020). Steady infiltration rate spatial modeling from remote sensing data and terrain attributes in southeast Brazil. *Geoderma Regional*, *20*, e00242. https://doi.org/10.1016/j.geodrs.2019.e00242

DeLaune, P. B., Mubvumba, P., Lewis, K. L., & Keeling, J. W. (2019). Rye cover crop impacts soil properties in a long-term cotton system. *Soil Science Society of America Journal*, *83*(5), 1451-1458. https://doi.org/10.2136/sssaj2019.03.0069

Dobarco, M. R., McBratney, A., Minasny, B., & Malone, B. (2021). A framework to assess changes in soil condition and capability over large areas. Soil Security, 4, 100011. https://doi.org/10.1016/j.soisec.2021.100011

Fontana, M. B., Novelli, L. E., Sterren, M. A., Uhrich, W. G., Benintende, S. M., & Barbagelata, P. A. (2021). Long-term fertilizer application and cover crops improve soil quality and soybean yield in the Northeastern Pampas region of Argentina. *Geoderma*, *385*, 114902. https://doi.org/10.1016/j.geoderma.2020.114902

Friendly, M. (2007). HE plots for multivariate linear models. *Journal of Computational and Graphical Statistics*, *16*(2), 421-444. https://doi.org/10.1198/106186007X208407

Guo, L., Linderman, M., Shi, T., Chen, Y., Duan, L., & Zhang, H. (2018). Exploring the sensitivity of sampling density in digital mapping of soil organic carbon and its application in soil sampling. *Remote Sensing*, *10*(6), 888. https://doi.org/10.3390/rs10060888

Gutknecht, J., Journey, A., Peterson, H., Blair, H. and Cates, A. (2022), Cover crop management practices to promote soil health and climate adaptation: Grappling with varied success from farmer and researcher observations. J. Environ. Qual.. Accepted Author Manuscript. https://doi.org/10.1002/jeq2.20383

Hartemink, A.E.; McBratney, A.; de Lourdes Mendonça-Santos, M. Digital Soil Mapping with Limited Data; Springer Science & Business Media: Berlin, Germany, 2008.

Helgason, B. L., Walley, F. L., & Germida, J. J. (2010). No-till soil management increases microbial biomass and alters community profiles in soil aggregates. *Applied Soil Ecology*, 46(3), 390-397. https://doi.org/10.1016/j.apsoil.2010.10.002

Jiang, X., Wright, A. L., Wang, J., & Li, Z. (2011). Long-term tillage effects on the distribution patterns of microbial biomass and activities within soil aggregates. *Catena*, 87(2), 276-280. https://doi.org/10.1016/j.catena.2011.06.011

Keeney, D.R. & Nelson, D. W. (1982). Nitrogen-inorganic forms. In Page, A.L., R.H. Miller and D.R. Keeney (Eds.) Methods of Soil Analysis. Part 2 – Chemical and microbiological properties. (2nd edition). Agronomy 9:643-698. https://doi.org/10.2134/agronmonogr9.2.2ed.c33

Krupek, F. S., Redfearn, D., Eskridge, K. M., & Basche, A. (2022). Ecological intensification with soil health practices demonstrates positive impacts on multiple soil properties: A large-scale farmer-led experiment. *Geoderma*, 409, 115594. https://doi.org/10.1016/j.geoderma.2021.115594.

Kuzyakov, Y., & Zamanian, K. (2019). Reviews and syntheses: Agropedogenesis–humankind as the sixth soil-forming factor and attractors of agricultural soil degradation. *Biogeosciences*, *16*(24), 4783-4803. https://doi.org/10.5194/bg-16-4783-2019

Lehmann, J., Bossio, D. A., Kögel-Knabner, I., & Rillig, M. C. (2020). The concept and future prospects of soil health. *Nature Reviews Earth & Environment*, *1*(10), 544-553.

Lenth, R. V. (2016). Least-Squares Means: The R Package lsmeans. *Journal of Statistical Software*, 69(1), 1-33. doi:10.18637/jss.v069.i01

Maharjan, B., & Das, S. (2021). Reference Ecological Unit: A Land Classification Unit for Comparative Soil Studies. *The Earth and Space Science Open Archive (ESSOAr)*. https://doi.org/10.1002/essoar.10508283.1

Maharjan, B., Das, S., & Acharya, B. S. (2020). Soil health gap: A concept to establish a benchmark for soil health management. *Global Ecology and Conservation*, 23, e01116. https://doi.org/10.1016/j.gecco.2020.e01116

Mbuthia, L. W., Acosta-Martínez, V., DeBruyn, J., Schaeffer, S., Tyler, D., Odoi, E., ... & Eash, N. (2015). Long term tillage, cover crop, and fertilization effects on microbial community structure, activity: Implications for soil quality. *Soil Biology and Biochemistry*, *89*, 24-34. https://doi.org/10.1016/j.soilbio.2015.06.016

Moebius-Clune, B.N., D.J. Moebius-Clune, B.K. Gugino, O.J. Idowu, R.R. Schindelbeck, A.J. Ristow, et al. 2016. Comprehensive assessment of soil health—The Cornell framework manual. 3rd ed. Cornell Univ., Geneva, New York.

Nebraska Extension On-Farm Research. 2021. Cover crop studies. On-Farm research results. pp. 142-182. Available at https://on-farm-research.unl.edu/pdfs/research/result-publications/2021research-results.pdf

Nelson, D. W., & Sommers, L. E. (1996). Total carbon, organic carbon, and organic matter. *Methods of soil analysis: Part 3 Chemical methods*, *5*, 961-1010. https://doi.org/10.2136/sssabookser5.3.c34

Nimmo, J.R., and Perkins, K.S.. 2002. Aggregate stability and size distribution. In: J.H. Dane, and G.C. Topp, editors, *Methods of soil analysis. Part 4*. SSSA Book Ser. 5. SSSA, Madison, WI. p. 317– 327.

Pellant, M., Shaver, P., Pyke, D.A., Herrick, J. E. (2005) Interpreting indicators of rangeland health, version 4, Technical Reference 1734-6. US Department of the Interior, Bureau of Land Management, National Science and Technology Center, Denver, CO. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1043944.pdf

Pennock, D., Yates, T., & Braidek, J. (2008). Soil sampling designs. *Soil sampling and methods of analysis*, *2*, 25-37.

R Core Team (2020). R: A language and environment for statistical computing. https:// www.R-project.org/ (accessed 2 March 2021).

Reynolds, W.D., Elrick, D.E. & Youngs, E.G (2002). Field methods (vadose and saturated zone techniques). p. 817-877. In J.H. Dane and G. C. Topp. (Eds.) Methods of soil analysis. Part 4. Agron. Monogr. 5. SSSA, Madison, WI.

Ruis, S. J., Blanco-Canqui, H., Koehler-Cole, K., Jasa, P. J., Slater, G., Elmore, R. W., & Ferguson, R. B. (2020). Winter cover crop root biomass yield in corn and soybean systems. *Agrosystems, Geosciences & Environment*, *3*(1), e20101.

Six, J., Bossuyt, H., Degryze, S., Denef, K. (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil Tillage Res*. 79, 7–31. https://doi.org/10.1016/J.STILL.2004.03.008.

Soil Survey Staff, 1999. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. 2nd edition. Natural Resources Conservation Service. U.S. Department of Agriculture Handbook 436.

Schipanski, M. E., Barbercheck, M., Douglas, M. R., Finney, D. M., Haider, K., Kaye, J. P., ... & White, C. (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

Smith, M. (2020). 2019-2020 Annual Report Cover Crop Survey. Available at https://www.sare.org/wp-content/uploads/2019-2020-National-Cover-Crop-Survey.pdf

Smith, R. E. (1999). Rapid measurement of soil sorptivity. *Soil Science Society of America Journal*, *63*(1), 55-57. https://doi.org/10.2136/sssaj1999.03615995006300010009x

Sprunger, C.D., Oates, L. G., Jackson, R.D.,&Robertson, G. P. (2017). Plant community composition influences fine root production and biomass allocation in perennial bioenergy cropping systems of the upper Midwest, USA. *Biomass and Bioenergy*, *105*, 248–258. https://doi.org/10.1016/j.biombioe.2017.07.007

Sprunger, C. D., Martin, T., & Mann, M. (2020). Systems with greater perenniality and crop diversity enhance soil biological health. *Agricultural & Environmental Letters*, *5*(1), e20030.

Stewart, R.D., Jian, J., Gyawali, A.J., Thomason, W.E., Badgley, B.D., Reiter, M.S., Strickland, M.S. (2018). What we talk about when we talk about soil health. *Agric. Environ. Lett*. 3 (1), 180033. https://doi.org/10.2134/ael2018.06.0033

Stringham, Tamzen K., William C. Krueger, and Patrick L. Shaver. "State and transition modeling: an ecological process approach." *Rangeland Ecology & Management/Journal of Range Management Archives* 56.2 (2003): 106-113.

Stumpf, L., Pauletto, E. A., & Pinto, L. F. S. (2016). Soil aggregation and root growth of perennial grasses in a constructed clay minesoil. *Soil and Tillage Research*, *161*, 71-78.

Tabatabai, M. A. (1994). Soil enzymes. *Methods of soil analysis: Part 2 Microbiological and biochemical properties*, *5*, 775-833. https://doi.org/10.2136/sssabookser5.2.c37

Thomas, G. W. (1983). Exchangeable cations. In A. L. Page et al. (Eds.) *Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties* (pp.159-165). https://doi.org/10.2134/agronmonogr9.2.2ed.c9

Tiemann, L. K., & Grandy, A. S. (2015). Mechanisms of soil carbon accrual and storage in bioenergy cropping systems. *Global Change Biology Bioenergy*, *7*(2), 161–174. https://doi.org/10.1111/gcbb.12126

Tisdall, J. M., & OADES, J. M. (1982). Organic matter and water-stable aggregates in soils. *Journal of soil science*, *33*(2), 141-163.

USDA-ARS Yield Editor. Available online: https://www.ars.usda.gov/research/software/?modeCode=50-70-10-00 (accessed on 25 August 2021).

USDA-NRCS, 2011. Planting Specification Guide: Cover Crop NH-340. U.S. Department of Agriculture Natural Resources Conservation Service. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1081555.pdf (accessed 5 July 2022).

Welch, R. Y., Behnke, G. D., Davis, A. S., Masiunas, J., & Villamil, M. B. (2016). Using cover crops in headlands of organic grain farms: Effects on soil properties, weeds and crop yields. *Agriculture, Ecosystems & Environment*, *216*, 322-332. https://doi.org/10.1016/j.agee.2015.10.014

Williams, A., Jordan, N. R., Smith, R. G., Hunter, M. C., Kammerer, M., Kane, D. A., ... & Davis, A. S. (2018). A regionally-adapted implementation of conservation agriculture delivers rapid improvements to soil properties associated with crop yield stability. *Scientific reports*, *8*(1), 1-8. https://doi.org/10.1038/s41598-018-26896-2

Williams, H., Colombi, T., Keller, T. (2020). The influence of soil management on soil health: an on-farm study in southern Sweden. *Geoderma* 360, 114010. https://doi.org/10.1016/j.geoderma.2019.114010.

Wills, S., Williams, C., Seybold, C., Scheffe, L., Libohova, Z., Hoover, D., ... & Brown, J. (2017). Using soil survey to assess and predict soil condition and change. In *Global soil security* (pp. 123-135). Springer, Cham. https://doi.org/10.1007/978-3-319-43394-3_11

Wood, S. A., & Bowman, M. (2021). Large-scale farmer-led experiment demonstrates positive impact of cover crops on multiple soil health indicators. *Nature Food*, *2*(2), 97-103. https://doi.org/10.1038/s43016-021-00222-y

Wood, S. A., & Blankinship, J. C. (2022). Making soil health science practical: Guiding research for agronomic and environmental benefits. *Soil Biology and Biochemistry*, 108776.

Yoder, R. E. (1936). A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses 1. *Agronomy Journal*, *28*(5), 337-351. https://doi.org/10.2134/agronj1936.00021962002800050001x

CHAPTER 4 : CARBON AND NITROGEN CONTENT IN COVER CROP ON-FARM EXPERIMENTS USING SOIL ORGANIC MATTER FRACTIONS AND REFERENCE SITES

This chapter is currently under preparation for publication: Krupek, F. S., Kaiser, M., Redfearn, D., & Basche, A. "Carbon and nitrogen content in cover crop on-farm experiments using soil organic matter fractions and reference sites"

Abstract

The identification of soil organic matter (SOM) benchmarks along gradients of land intensification is critical to guide conservation goals towards realistic improvements in soil carbon (C) and nitrogen (N) storage and cycling. In this study, we clarified (a) how the C and N concentration within SOM fractions of distinct ecological relevance responded to soil management representing a cropland-grassland gradient and (b) how these operationally defined fractions affected soil physicochemical and biological properties. We compared sites with annual row crop rotations with and without cover crops (i.e., cropland soils) with perennial grassland sites (i.e., reference soil) by sampling near-surface soils (0-5 cm depth) from statewide on-farm cover crop experiments replicated across four agro-ecoregions in Midwest USA. We found that C content of free particulate organic matter (free-POM) and water-extractable OM (WEOM) of reference soils were 58-76% and 31-59% greater than those of the cropland soils. Differences in N content of WEOM and aggregate occluded POM (o-POM) due to soil management were observed in two of the four sites. These reference soils had two to three times greater N than cropland soils. Differences in cropland changes in C and N content relative to reference soils were observed for irrigated and no-till sites and medium to fine texture soils. Free and o-POM C and N were strongly associated with aggregate stability, water infiltration, and enzyme activity, whereas C and N contents of WEOM and MAOM were correlated with soil's ability to hold onto essential nutrients (e.g., calcium, magnesium, potassium, and sodium). Although the potential of cover crops to drive changes on ecologically meaningful SOM fractions is less pronounced in the short (3-yr) term, the findings demonstrate the potential of continuous living cover as an approach to agroecosystem design for improved SOM C and N dynamics and related soil functions.

Keywords

Soil organic matter; Cover crop; Carbon; Nitrogen

Abbreviations

C, carbon; free-POM, free particulate organic matter; MAOM, mineral-associated organic matter; N, nitrogen; POM, particulate organic matter; o-POM, occluded POM; OM, organic matter; SOM, soil organic matter; SOC, soil organic carbon

Introduction

Soil management that can increase carbon (C) sequestration and nitrogen (N) retention is critical for mitigating climate change (Smith et al., 2019). Emerging interest in climate-friendly approaches to land use and soil management represents a re-evaluation of decades of non-sustainable management practices that have led to soil degradation through erosion and soil organic matter (SOM) depletion (Lal, 2020; Prokopy et al., 2020). Recently, governmental and private-led initiatives have encouraged soil C sequestration with financial incentives and carbon market programs (Fleming et al., 2019; Wolf and Ghosh, 2020). This has increased interest in “climate-smart” management practices as a means to reduce agroecosystem C and N footprint (Schulte et al., 2016; Buck and Palumbo-Compton, 2022).

In agroecosystems, SOM plays a critical role in crop productivity due to positive effects on water and nutrient retention, bulk density, soil structure, and microbial diversity as well as in mitigation of climate change by functioning as a reservoir of C and N if retained in soil (Knicker, 2011; Lehmann and Kleber, 2015). SOM is a mixture of organic compounds at various degrees of decomposition, which are continuously processed by soil decomposer communities and vary in origin, molecular size, elemental composition, oxidation, and solubility (Cotrufo et al., 2015; Lehmann and Kleber, 2015). The mean residence time of SOM and its protection against microbial decay in aerated topsoils, which is critical in SOM functioning as a C-and N-sink, are thereby mainly affected by processes such as associations with mineral surfaces and occlusion in soil aggregates (Lehmann and Kleber, 2015; Cotrufo and Lavallee, 2022).

Research on soil management effects on C and N cycling often apply operationally defined procedures that partition SOM into distinct fractions (Cotrufo and Lavallee, 2022; Lavallee et al., 2020; Lugato et al., 2021; Rocci et al., 2021). For this, the separation of bulk SOM into ecologically meaningful fractions such as free particulate organic matter (free-POM), aggregate-occluded POM (o-POM), water-extractable organic matter (WEOM), and mineral-associated organic matter (MAOM) is becoming increasingly deployed (Chen et al., 2020; Daly et al., 2021; Jilling et al., 2020). As an ecologically meaningful fraction dominated by plant-derived residues, POM is the initial substrate in the SOM decomposition continuum. Soil decomposer communities continuously process POM, leading to smaller molecular size fractions such as WEOM and the development of predominantly microbial-derived compounds largely contributing to the MAOM fraction (Grandy and Neff, 2008; Hatton et al., 2012). Occlusion of POM, WEOM, and MAOM in aggregates of different sizes can further alter their soil ecological function by affecting their location in the soil matrix and reducing their accessibility to enzymatic breakdown (Wagai et al., 2009).

Fractionation methods applied to partition and isolate SOM sub-compartments offer insights not only in SOM responses to global environmental changes (Rocci et al., 2021), but also on how soil management alters the accrual and distribution of C and N within soil. The POM fraction, for example, is sensitive to changes in soil and crop management in the short-term (Gartzia-Bengoetxea et al., 2009; Spargo et al., 2011; Willson et al., 2001) and can serve as an early indicator of effects derived from decreased tillage intensity and cover cropping (Chan et al., 2002; Chivenge et al., 2007). The WEOM fraction is also considered to be sensitive to short-term changes in management and is relevant for the transport of water, oxygen, nutrients, and substrate to microbial hotspots within the soil matrix (Rabbi et al., 2016), with direct influence on soil microbial growth (Abiven et al. 2007; Bertora et al., 2018; Bhattacharyya et al. 2012). Even though representing only a small portion of total SOM (Chantigny, 2003), water-soluble OM is in part easily decomposable and involved in many soil processes by shaping microbial diversity (Bu et al., 2020) and more specifically bacterial community composition (Guo et al., 2015; Munkholm et al., 2016). MAOM is considered a long-term (i.e., >100 years) sink for C and N (Trumbore, 2009). However, recent studies have shown that MAOM can also be dynamic even at shorter timescales (i.e. <10 years), particularly in agricultural systems where anthropogenic perturbations and residue removal cause depletion of POM and accumulation of C and N within MAOM (Denef et al., 2013; Jilling et al., 2020; Yu et al., 2022). Nevertheless, studies on SOM fractionation, particularly isolating more labile and water-extractable fractions, are mainly derived from temperate forest soils and to a lesser extent from grassland and managed soils (Chantigny, 2003). Additionally, studies in agroecosystems mostly focus on C stored within POM, whereas few studies have estimated N and their distribution across more protected long-term sinks such as the MAOM (Jilling et al., 2020) despite the large quantitative importance of this fraction (usually >50% of SOM).

Cover crops have been promoted in Midwestern US agroecosystems as a way to meet several soil health goals (Bowman et al., 2022; Gutknecht et al., 2022), more specifically as climate adaptation tools to increase soil C sequestration and improve soil N management (Griscom et al., 2017; McClelland et al., 2021; Poeplau and Don, 2015). According to the last Census of Agriculture, cover crop acreage doubled from 2012 to 2017 in many agricultural states in the Midwest USA (USDA-NASS, 2019). Recent predictions using satellite data reveal that the cover crop adoption in the region in 2021 is four times that of 2011 (Zhou et al., 2022). This demonstrates the growing interest in the adoption of more environmentally sound management practices, in part due to state, federal, and conservation programs with an emphasis on approaches to climate change mitigation and adaptation (Bowman & Lynch, 2019; Wallander et al., 2021). As a climate-smart strategy that enhances SOM dynamics, cover crops can affect SOM amount and retention through two distinct conceptual pathways (Cotrufo et al., 2015; Cotrufo and Lavallee, 2022). In one pathway, cover crop-derived litter residues are input sources for POM (Haddix et al., 2016). In the other pathway, water-soluble OM, primarily through leaching from decomposing aboveground cover crop residues, from root exudates, and root litter decomposition are input sources for MAOM (Austin et al., 2017; Kallenbach et al., 2016; Samson et al., 2020). By extending the period in which plant roots interact with the soil environment, cover crop-derived above and belowground inputs can contribute to soil organic C and N cycling by providing greater diversity in root-derived OM inputs (Austin et al., 2017) and supporting microbial growth. This can lead to the stabilization of microbial necromass contributing to increased SOM amount in the rhizosphere (Kallenbach et al., 2016; Miltner et al., 2012).

The inclusion of cover crops on farms in the Midwest USA is a strategy to establish year-round soil cover in less diversified annual row cropping systems (primarily maize- and soybean-dominated) and to broadly reduce negative effects on soil health derived from the common practice of land conversion from grassland to managed agroecosystems (Seifert et al., 2018; Wright and Wimberly, 2013). As an ecosystem with the majority (approximately 90%) of C stored belowground as root biomass and SOC, grasslands play a vital role in SOM cycling and storage in soils (Bai and Cotrufo, 2022; Bardgett et al., 2021). Thus agricultural practices that promote continuous living roots throughout the year such as cover crops offer an approach to agroecosystem design that mimics ecosystem C and N dynamics of native grassland (Basche and Edelson, 2017). However, most of the recent research efforts have focused on responses of the bulk soil or SOM fractions to the incorporation of cover crops compared to winter fallow (i.e., no cover crop). In contrast, much less is known about SOM benchmarks along gradients of intensified land use and management that included site-specific reference conditions under maximum and minimum disturbance. Therefore, a comprehensive assessment of soil C and N dynamics using SOM fractions that account for soil and climate variabilities could benefit the entire Northern Great Plains in their agricultural innovations and climate-smart strategies to enhance soil health and mitigate climate change.

In light of the identified knowledge gaps, the objectives of this study were to clarify how C and N associated with different SOM fractions responded to three years of cover crops in annual row crop rotation as compared with systems without cover crops and sites representing perennial, grassland (i.e., reference conditions). Further, we aimed to clarify how changes in SOM fractions were related to soil physical, chemical, and biological properties. We hypothesized that three years after cover crop integration into annual cropping systems would increase C and N stored especially in POM and WEOM fractions to levels that are in between systems with the highest management intensity (i.e., no cover crop) and lowest management intensity (i.e., grassland reference sites). Further, we expected that POM and WEOM fractions would exert a stronger effect on soil edaphic characteristics in grassland and cover crop-based soils as compared with annual cropping systems without cover crops.

Materials and Methods

Study sites description

Four multi-year on-farm experiments adjacent to four grassland sites across Eastern and Central Nebraska were used for this study (Figure 4.1A). Soils across sites were predominantly classified as Mollisols, Entisols, and Alfisols (Soil Survey Staff, 1999) (Table 4.1). Sites have a varied range of soil textures (Figure 4.1B) that were categorized as coarse (e.g., sand, loamy sand, and sandy loam), medium (e.g., loam, silt loam, silt, sandy clay loam), or fine (e.g., clay loam, silty clay loam, sandy loam, silty clay, and clay) for data analysis purposes. On-farm fields were irrigated in the summer except for Colfax site (Table 4.1). All grassland sites were non-irrigated. Historical annual precipitation and temperature (10-yr average) for each site are 633 mm and 9.7 °C (Colfax), 483 mm and 9.4 °C (Greeley), 463 mm and 10.2 °C (Howard), and 465 mm and 10.5 °C (Merrick) according to information from nearby Nebraska Mesonet weather station retrieved from the High Plains Regional Climate Center (HPRCC, https://hprcc.unl.edu/).

Experimental design and soil management treatments

Cover crop experiments on farms were initiated in 2016 in partnership with the Natural Resources Conservation Service (USDA-NRCS) and the University of Nebraska On-Farm Research Network (Krupek et al., 2022a). All on-farm sites utilized a randomized complete block design with multispecies cover crop and a control (no cover crop check) (Figures 4.1C and 1D). Trials had at least a 27-hectare field (to obtain at least a 1.5-hectare minimum plot size), and the most common layout was a 12-strip format (n = 6 for each treatment). In a corn (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.] rotation, farmers introduced cover crop mixtures of cool-season small grain cereals, legumes, brassicas, and warm-season summer annual grasses based on NRCS guidelines (USDA-NRCS, 2011). Cover crop mixtures were planted in the fall and terminated with herbicides in the spring following grower's common practices. Cover crop management considerations (e.g., species selection, planting and termination dates) were site-specific (Table 4.1), representing possible options for the incorporation of cover crops into cropping systems in Eastern and Central Nebraska farmland (Nebraska Extension On-Farm Research, 2021). Crop residues (cover crop, corn, and soybean) during the multi-year on-farm experimentation were left on the soil surface after termination or harvest. Full details of on-farm study and management practices (i.e., tillage practices, irrigation, crop planting and termination, extensionist-reported cover crop biomass) are provided in Table 4.1.

In addition to the on-farm experiments (i.e., cover vs. no cover crop randomized strip trials), sites from nearby farmland – non-grazed grassland areas with a minimum degree of anthropogenic modification of soil properties due to management or land use change – were identified to determine soil health benchmarks as suggested by Maharjan et al. (2020) and Maharjan and Das (2021). These reference sites were all grass-dominated and located within ~ 3 km of the on-farm trials (Figure 4.1C). Selection of reference sites accounted for soil and climate variabilities within on-farm trials. Each reference site had functional Ecological Site Description vegetation with major components of the historical climax plant community. According to state and transition models (Bestelmeyer et al., 2017), field assessments showed vegetation communities in Native/Invaded Grass State 2.1, Switchgrass/Prairie Sand Reed Plant Community 1.2, Native/Invaded Mix State Community 2.2–Codominant, and Native/Invaded Grass State 2.1 for reference soils in Greeley, Merrick, Colfax, and Howard respectively (Table 4.1). Thus, to describe cropland soil function compared with its local native potential, the following soil management treatments representing an intensification gradient were included in our analysis: (i) corn-soybean rotation with a bare fallow period (soil management: no cover crop), (ii) corn-soybean rotation with multispecies cover crop (soil management: cover cop), and (iii) minimum disturbed grassland sites (soil management: reference soil).

Soil sampling design

Soil samples were collected three years after initial cover crop planting at the on-farm sites. Soil sampling occurred in July 2019, when on-farm plots were at or near soybean (Glycine max (L.) Merr.) growth stage R6 (full seed). We sampled surface soils (0-5 cm depth) using a soil sampler of a core diameter of 32 mm model PN012, JMC Backsaver N-2 handle (JMC Soil samplers, Newton, IA, USA). We adopted a near-surface approach to soil sampling because cover crop effect on C and N dynamics within SOM fractions are expected to be most pronounced at 0-5 cm depths (Duval et al., 2016; Jilling et al., 2020; Sastre et al., 2018). Additionally, cover crop studies conducted in the same on-farm sites (Krupek et al., 2022b) or in the same agro-ecoregion (Ruis et al., 2020; Koehler-Cole et al., 2020; Anuo et al., 2023) adopted a topsoil sampling depth, which adds potential to improve our results interpretation in relation to the published studies.

A total of 88 sampling points across all on-farm experiments and reference sites were identified using the USDA-NRCS Web Soil Survey. Sampling points were identified on a representative basis of soil type, plot size, and replication by selecting 2-3 soil types representing at least 50% of the site area. To minimize spatial soil variation, in each sampling point, 10 soil cores were collected around a 6-m x 24-m sample area (Figure 4.1E), composited, and shipped on ice to both a commercial lab (Ward Laboratories - Kearney, NE) and the University of Nebraska-Lincoln soil laboratory.

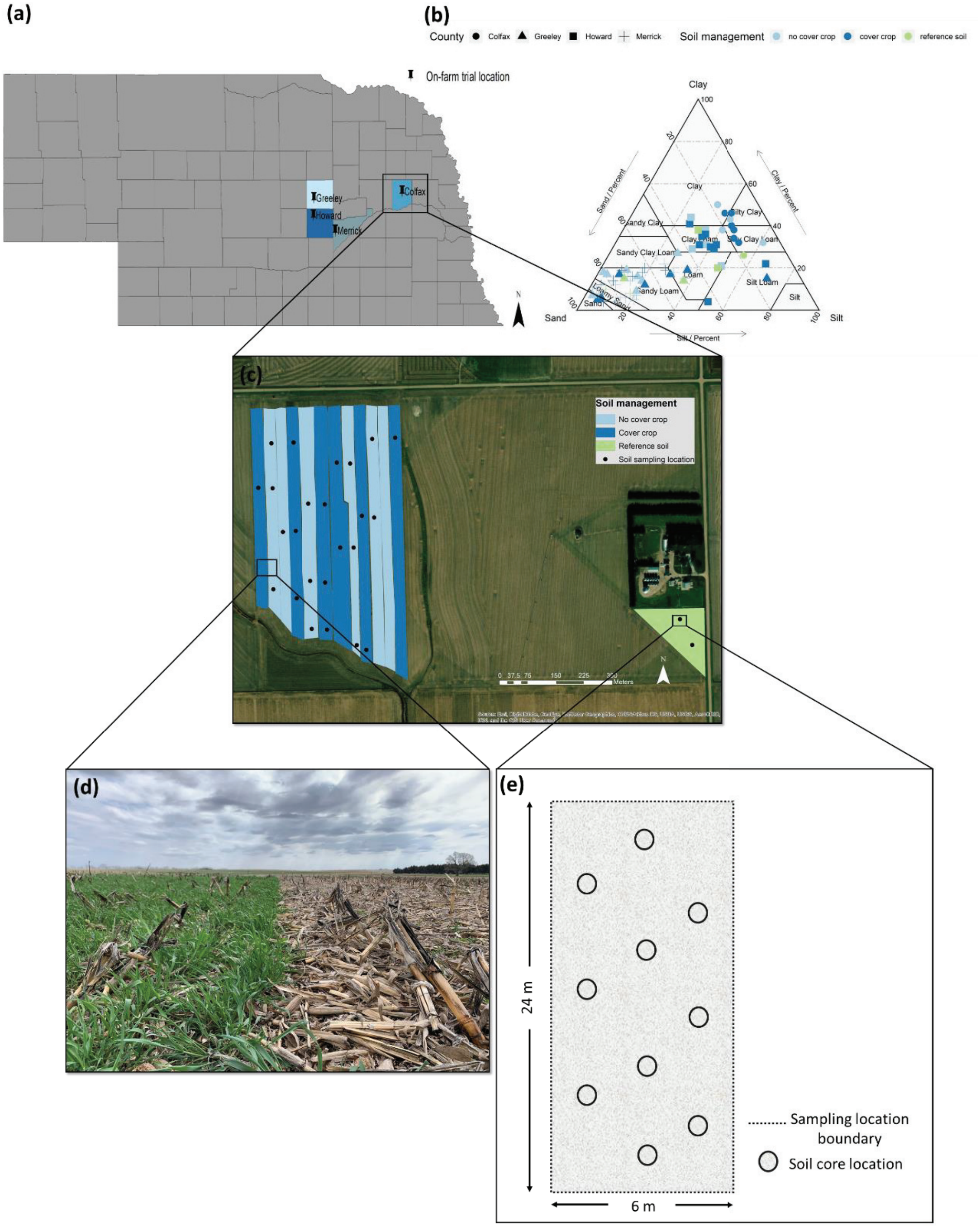

Figure 4.1. (A) Map of the four on-farm trials participating in the Nebraska USDA-NRCS Soil Health Initiative included in this analysis. (B) Soil texture for each of the soils sampled in this analysis displayed in a texture triangle. (C) Map of experimental design and soil management treatments (no cover crop, cover crop, reference soil) common to all on-farm trials. (D) On-farm treatment plots with multispecies cover crop (left) vs no cover crop (right). (E) Layout showing the 6 m × 24 m area within each plot used for soil sampling.

Table 4.1. Details of soil order, texture, crop and soil management, field area, state of reference soil, and average plot size of the four on-farm sites included in this study.

Farm county	Soil order	Soil texture (% clay content)	Cover crop mixtures	2018-2019 cover crop planting & termination dates	2019 spring cover crop biomass (kg ha^{-1})	2019 soybean planting	Tillage (years)	Summer irrigation	State of reference soil[1]	Mean plot size (width x length)
Greeley	Entisols and Alfisols	Coarse and Medium (5-27)	56 kg ha^{-1} cereal rye (*Secale cereale L.*), 1.12 kg ha^{-1} forage collards (*Brassica oleracea var. viridis)*, 1.12 kg ha^{-1} turnips (*B. rapa L. var. rapa (L.) Thell*), 1.12 kg ha^{-1} rapeseed (*Brassica napus*), and 1.12 kg ha^{-1} kale (*Brassica oleracea sabellica*)	November 17, 2018 and June 1, 2019	158.84	May 15	No-till (10)	Yes	Native/Invaded Grass State 2.1	74m x 412 m
Howard	Mollisols	Fine and Medium (20-44)	37 kg ha^{-1} cereal rye (*Secale cereale L.*), 0.9 kg ha^{-1} turnips (*B. rapa L. var. rapa (L.) Thell*), 0.7 kg ha^{-1} African cabbage (*Cleome gynandra*), 0.6 kg ha^{-1} forage collards (*Brassica oleracea var. viridis)*, 1.8 kg ha^{-1} rapeseed (Brassica napus), 1.2 kg ha^{-1} eco-till radish (*Raphanus sativus var. niger*), 1.2 kg ha^{-1} sunflowers (*Helianthus annuus*), 1.1 kg ha^{-1} safflowers (*Carthamus tinctorius*), 1.8 kg ha^{-1} hairy vetch (*Vicia villosa* Roth), and 1.1 kg ha^{-1} lentil (*Ervum lens* L.)	September 21, 2018 and May 14, 2019	3,077.00	May 16	No-till (3)	Yes	Native/Invaded Grass State 2.1	52 m x 573 m
Merrick	Entisols and Mollisols	Coarse and Medium (10-26)	22 kg ha^{-1} cereal rye (*Secale cereale L.*), 22 kg ha^{-1} winter wheat (*Triticum aestivum*), 11 kg ha^{-1} triticale (*×Triticosecale Wittmack*), 1.1 kg ha^{-1} annual ryegrass (*Lolium multiflorum* Lam.), 5.6 kg ha^{-1} winter oats (*Avena sativa* L.), 3.4 kg ha^{-1} hairy vetch (*Vicia villosa* Roth), 0.6 kg ha^{-1} camelina (*Camelina sativa*), and 3.4 kg ha^{-1} winter lentil (*Ervum lens* L.)	October 14, 2018 and May 5, 2019	280.50	May 3	Strip-till	Yes	Switchgrass/Prairie Sand Reed Plant Community 1.2	24 m x 670 m
Colfax	Mollisols	Fine (26-50)	9 kg ha^{-1} winter wheat (*Triticum aestivum*), 9 kg ha^{-1} cereal rye (*Secale cereale L.*), 9 kg ha^{-1} triticale (*×Triticosecale Wittmack*), 1.1 kg ha^{-1} rapeseed (*Brassica napus*), 5.6 kg ha^{-1} winter oats (*Avena sativa* L.), 9 kg ha^{-1} winter barley (*Hordeum vulgare*), 1.1 kg ha^{-1} camelina (*Camelina sativa*), 1.1 kg ha^{-1} hairy vetch (*Vicia villosa* Roth), 2.8 kg ha^{-1} lentil (*Ervum lens* L.), and 1.1 kg ha^{-1} crimson clover (*Trifolium incarnatum*)	November 19, 2018 and May 10, 2019	NA	May 14	No-till (20)	No	Native/Invaded Mix State Community 2.2–Codominant	40 m x 623 m

[1] Based on field assessments of vegetation communities based on state and transition models (Bestelmeyer et al., 2017).

Soil property measurements and laboratory analysis

Analysis of soil edaphic characteristics – namely exchangeable bases, pH, soil texture, nitrate-nitrogen, and β-glucosidase activity – was conducted using standard methods in the commercial laboratory. In brief, soil texture was measured using the hydrometer method following Gee and Bauder (1986). Nitrate-nitrogen in soil extracts was measured through cadmium reduction method adapted from Keeney and Nelson (1982). The activity of β-glucosidase (mg of *p*-nitrophenol (PN) kg^{-1} soil h^{-1}) was assayed using air-dried soil (<5 mm) with *p*-nitrophenyl derivate substrate and incubated (37 °C) at their optimal pH (Tabatabai, 1994). Exchangeable bases were extracted from soil using pH 7, 1M NH_4OAc (Thomas, 1983). Extracts were analyzed for Ca^{2+}, Mg^{2+}, K^+, Na^+, and H^+ by ICP-OES and the cation exchange capacity (CEC) was calculated based on the sum of exchangeable base cations. Soil pH was measured in a 1:1 solution of soil to water using a desktop pH meter.

In each sample area, five consecutive measurements of initial water infiltration were conducted in the field and averaged for each sampling point according to Krupek et al. (2022b). Initial water infiltration (i.e., sorptivity) was measured using a 9.8-cm inner diameter open-ended metal ring following a method described by Smith et al. (1999). Single-ring infiltrometers were inserted to 5 cm depth in the soil, and the time for 75 ml of water to completely infiltrate was plugged into the sorptivity equation as described by Rakkar et al. (2019). Bulk density was determined using the core method (Blake & Hartge, 1986) for each sampling point at 0-5 cm soil depth. Finally, wet aggregate stability, expressed as mean weight diameter (MWD) of water-stable aggregates, was measured by the wet sieving method (Nimmo and Perkins, 2002) on the soil cores collected for SOM fractionation (air-dried samples), by using a modified version of the Yoder wet-sieving device (Yoder, 1936) from the University of Nebraska–Lincoln.

Soil organic matter fractionation

We employed a sequential fractionation procedure according to Remus et al. (2018) to separate bulk SOM into distinct sub-compartments (i.e., free-POM, macro- and micro-aggregate occluded POM, WEOM, and MAOM) based on differences in size, density, and solubility in water, properties that in turn, influence SOM turnover dynamics (Figure 4.2). First, 10 g of air-dried soil were gently crushed and passed through a 250 µm sieve. Free-POM was obtained by electrostatic attraction through repeated movement of a warmed and dry PVC petri-dish surface over the > 250 µm soil placed evenly on aluminum foil (Kaiser et al., 2009). In the next step, 5 g of the recombined soil (< 250 and > 250 µm) was gently dispersed in deionized water, at a target soil:water ratio of 1:10, to separate the remaining free-POM (< 250 µm). After the floating particles were recovered (i.e. free-POM < 250 µm), the remaining soil/water suspension was shaken for 12 h followed by centrifugation at 4,000 x g for 30 min and extraction of the free water-extractable OM fraction (WEOM) according to Kaiser et al. (2010).

In the subsequent steps, we applied a stepwise dispersion of aggregates with increased ultrasonic energy levels (i.e., time of ultrasonic energy application) to disintegrate aggregates of different stability (Figure 4.2). Incremental levels of sonication intensity were used to isolate aggregate occluded POM (macro and micro) from MAOM. This is based on the hypothesis that the relative mechanical stability of small aggregates or aggregate subunits is greater than that of larger aggregates; as such more energy is required in each consecutive subdivision of an aggregate into smaller fragments (Kaiser and Berhe, 2014). Ultrasonication was performed using a Digital Sonifier 250, a 120C CE converter, a disruptor horn, and a flat tip (Branson, Danbury, CT, USA). Briefly, the first extraction residue was mixed with 30 ml water to receive an initial low-energy sonication of 60 J cm^{-3} to disperse macro-aggregates (Amelung and Zech, 1999). After five minutes of sedimentation time, the supernatant was pipetted and passed through a 53 µm sieve to recover macroaggregate occluded-POM fraction (Kaiser et al., 2010). The time of the second and third sonication steps was increased aiming to deliver 440 and 500 J cm^{-3} of ultrasonic energy, respectively (Remus et al., 2018). Following the second sonication level, the suspension was passed through a 53 μm sieve to recover microaggregate occluded-POM fraction. Only the <53 μm fraction was subjected to an energy level of 500 J cm-3. Following the last sonication step, the soil suspension was passed through a 20 μm sieve; the material recovered on the sieve was considered 53-20 μm mineral particles. The material less than 20 μm was referred to as mineral particles <20 μm (MAOM). Fractions isolated in solid-state (i.e., free-POM, macro- and micro-aggregate occluded POM, and MAOM) were freeze-dried (Virtis Freezemobile 25XL-70, Gardiner, NY), weighted, and stored in glass vials until further analysis. C and N stored in these fractions were measured by dry combustion using CN elemental analyzer (Thermos Scientific, Waltham, MA, USA). C and N content and distribution within macro- and micro-aggregate occluded POM fractions were combined and presented as occluded POM (o-POM) for ease of results interpretation. The volume of filtrate used for quantifying the liquid state fraction (i.e., WEOM) was measured and stored in Amber HDPE plastic bottles at -20 °C. Samples were then measured for dissolved organic C and dissolved total N using a total organic C analyzer (OI Analytical Aurora, Baltimore, MD).

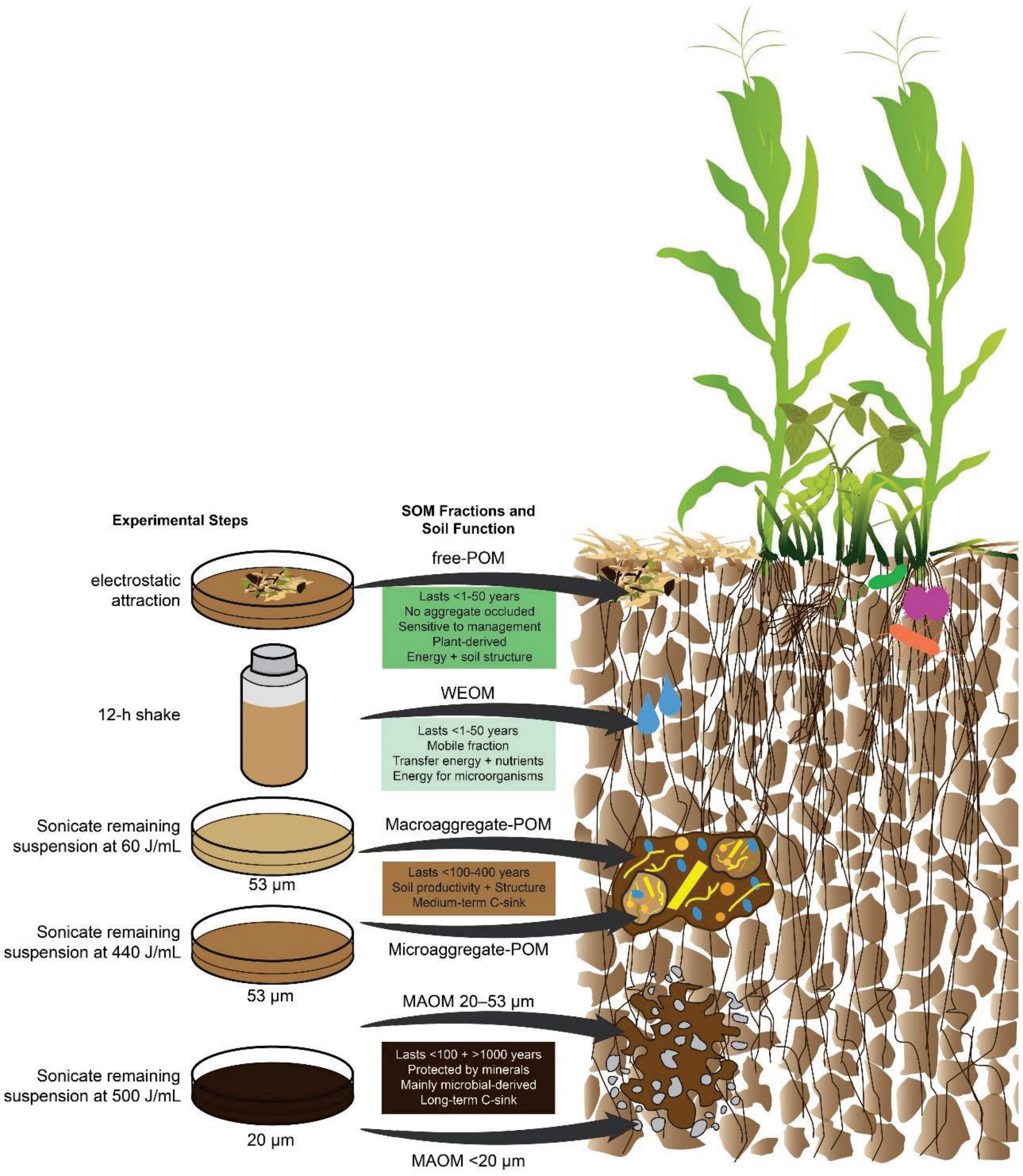

Figure 4.2. (A) Illustration of the employed fractionation procedure that combines electrostatic attraction, water extraction, sonication, and wet sieving (Remus et al., 2018). (B) Separated OM fractions and their soil ecological meaning. Artwork by Lana Koepke Johnson.

Statistical analysis

To address the first objective of this study, we fitted an analysis of variance model for the SOM variables (C and N content and distribution across bulk and SOM fractions) considering replication and soil management (e.g., cover crop, no cover crop, and reference soil) as fixed effects using aov function in R version 4.0.4 (R Core Team, 2020). We ran separate fixed effect models within each site due to differences in soil edaphic characteristics (e.g., texture), state of the selected reference soils, and on-farm management practices (e.g., tillage, irrigation) across cover crop on-farm trials (Table 4.1). Assessment of the residual QQ-plots did not reveal problems with the linearity of the fixed effects, homogeneity, and normality. Mean separation comparisons were performed using *lsmeans* package at a *p*-value of .10 (Lenth, 2016).

In the next step of the analysis, we calculated response ratios for all SOM variables to evaluate the gains or losses in cropland soil C and N functions relative to its local native potential. The response ratio represents the natural log of the bulk and SOM fractions C and N contents of cropland soils (e.g., cover crop and no cover crop) divided by the values of reference soil. Response ratios were calculated for all combinations of cropland and reference soil within each site, back-transformed from the natural log, and expressed as a percent changes from reference soil. Mixed model regression analysis were conducted to understand the relative effects of on-farm management (e.g., site-specific cover crop adoption, tillage, and irrigation practices), soil edaphic characteristics (e.g., texture), and state of reference soils on SOM C and N changes relative to reference soil.

To address the second and last objective of this study, we performed a principal component analysis (PCA) using the function *prcomp* in the package stats in the R software version 4.0.4 (R Core Team, 2018). This analysis was performed to further explore our dataset and understand the relationships between SOM fractions and soil physical, chemical, and biological properties. All sites were analyzed together because we were interested in broad-scale patterns, irrespective of site effects. Because the soil properties have different units and variances, PCA analysis was based on the correlation matrix, rather than the covariance matrix. All individual variables were checked for normality, confirming approximate multivariate normality and suitable use of linear ordination methods.

Results

Effects of management, texture and reference condition on soil C content in bulk soil and OM fractions

The mean bulk SOC content ranged from 10 to 44 g C kg^{-1} soil across Colfax, Greeley, Howard, and Merrick sites (Figure 4.3). Bulk soil organic C content values for reference soils were 21, 33 and 28 % greater than cropland systems (both cover crop and no cover crop) in Colfax, Greeley and Merrick sites, respectively, while no differences among soil management were observed for bulk soil organic C content in Howard site (Figure 4.3).

Within the SOM fractions analyzed, C content (i.e., g C fraction per kg soil) ranged from 2.5-14.15 g C kg^{-1} soil, 0.02-15.4 g C kg^{-1} soil, 0.07-0.35 g C kg^{-1} soil, and 0.8-13.8 g C kg^{-1} soil for free-POM, o-POM, WEOM, and MAOM respectively (Figure 4.3). Soil management had significant main effect on C content in SOM fractions, but responses were site- and fraction-specific (Figure 4.3). Main differences in free-POM C content due to soil management were observed in Greeley and Merrick sites, in which reference soils had on average 14.18 g C kg^{-1} soil that represents an increase in organic C by 76% (Greeley) and 59% (Colfax) compared to cropland soils (Figure 4.3). Similarly, WEOM C content values for reference soils were 60% greater than cropland systems (cover crop and no cover crop) in Colfax and 38% greater than annual cropping systems without cover crop in Howard site (Figure 4.3). Main differences in o-POM C content due to soil management were observed across all sites expect for Greeley, in which C content for reference soils were 57 to 92% greater than cropland systems (Figure 4.3). No differences in MAOM C content were attributed to changes in soil management. Averaged across the three soil managements tested, MAOM C content values for Colfax, Greeley, Howard and Merrick were 9.02 g C kg^{-1} soil, 3.15 g C kg^{-1} soil, 10.9 g C kg^{-1} soil, and 4.05 g C kg^{-1} soil, respectively (Figure 4.3). Mean C recovery was 74% across all sites, with the majority of bulk SOC recovered in the free-POM (32%) and MAOM (25%) fractions while a small, less than 1%, was recovered in the WEOM fraction (Figures S1 and S2). Across the all sites included in this analysis, C content of POM and WEOM were more sensitive to management changes than MAOM (Figure 4.3).

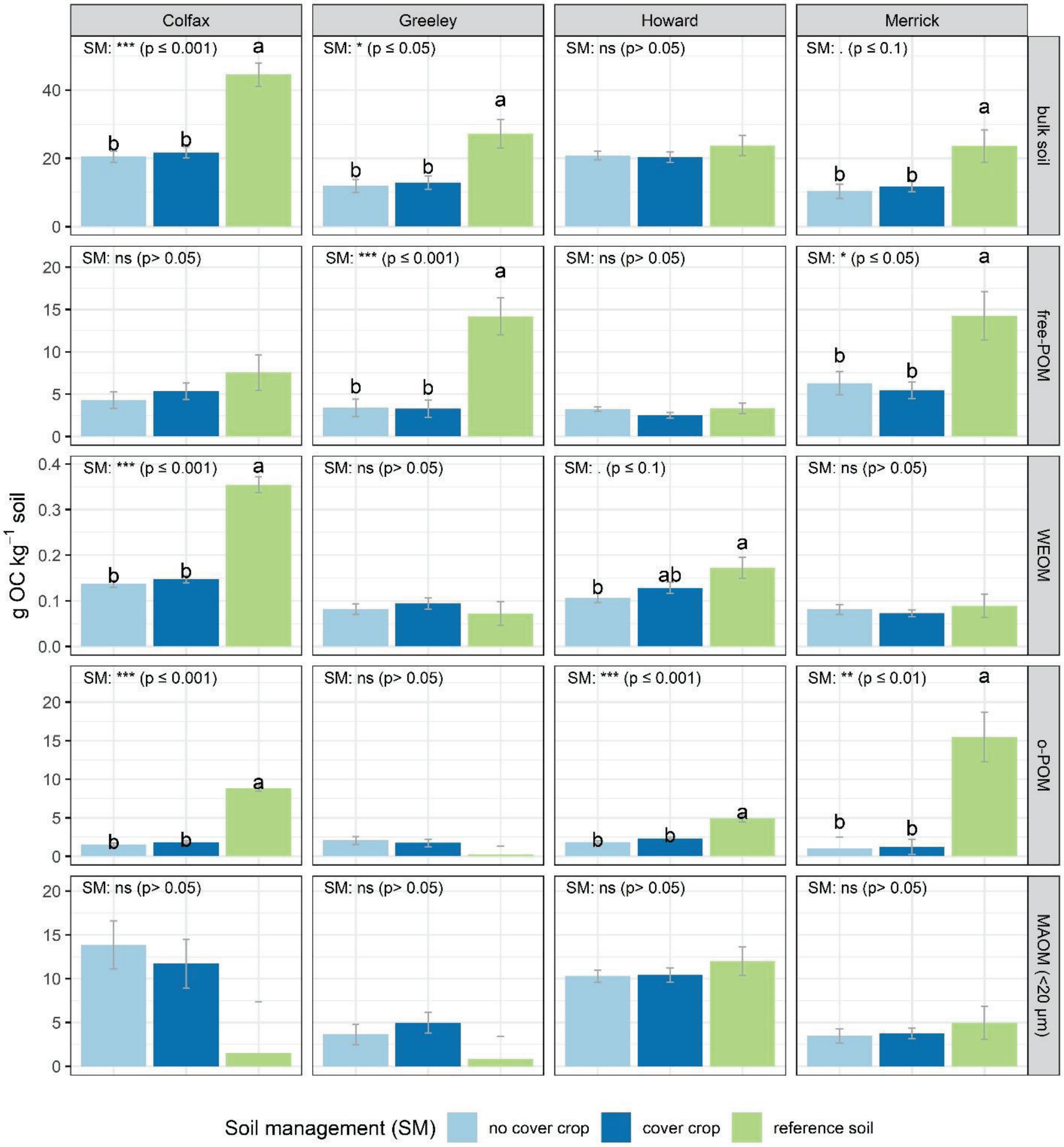

Figure 4.3. Effect of soil management on organic carbon content across bulk soil and SOM fractions in sites located in Colfax, Greeley, Howard, and Merrick. Error bars indicate mean standard error. ANOVA results for each site and fraction provided within the respective panel with significant main effects. Bars followed by similar letters indicate no significant differences ($p < 0.1$) among soil management within each SOM fraction according to Tukey test. Descriptors: free-POM= free particulate organic matter, WEOM = water extractable organic matter; o-POM = aggregate occluded POM; MAOM= mineral-associated organic matter.

The diversity in management (e.g., cover crop adoption and species selection, tillage, and irrigation practices), soil edaphic characteristics (e.g., texture), and state of reference soils across the four sites included in our analyzes (Table 4.1) allowed us to explore the how these factors might affect gains or losses in cropland soil C functions relative to its local native potential (Figure 4.4). In general, significant differences in soil organic C between cover crop and no cover crop treatments were not detected (Figure 4.3). This means that the effects of cover crop adoption on C content in bulk and SOM fractions was less pronounced than cropland-grassland transition and the differences soil texture, tillage and irrigation practices adopted on farms as well the selection of reference sites (Figure 4.4). Bulk soil organic C declines in cropland relative to reference soil were the highest in non-irrigated, coarse textured sites under long-term (20 yrs) no-till (Figure 4.4). Declines in cropland free-POM C relative to reference soil was lower in fine than medium and coarse texture soils (Figure 4.4). Similarly, WEOM C changes in cropland relative to reference soil were higher in irrigated than non-irrigated sites and in medium to fine texture than coarse soils (Figure 4.4). MAOM C changes relative to reference soil for sites that were continuously adopting no-till were higher than those for sites practicing strip-tillage (Figure 4.4).

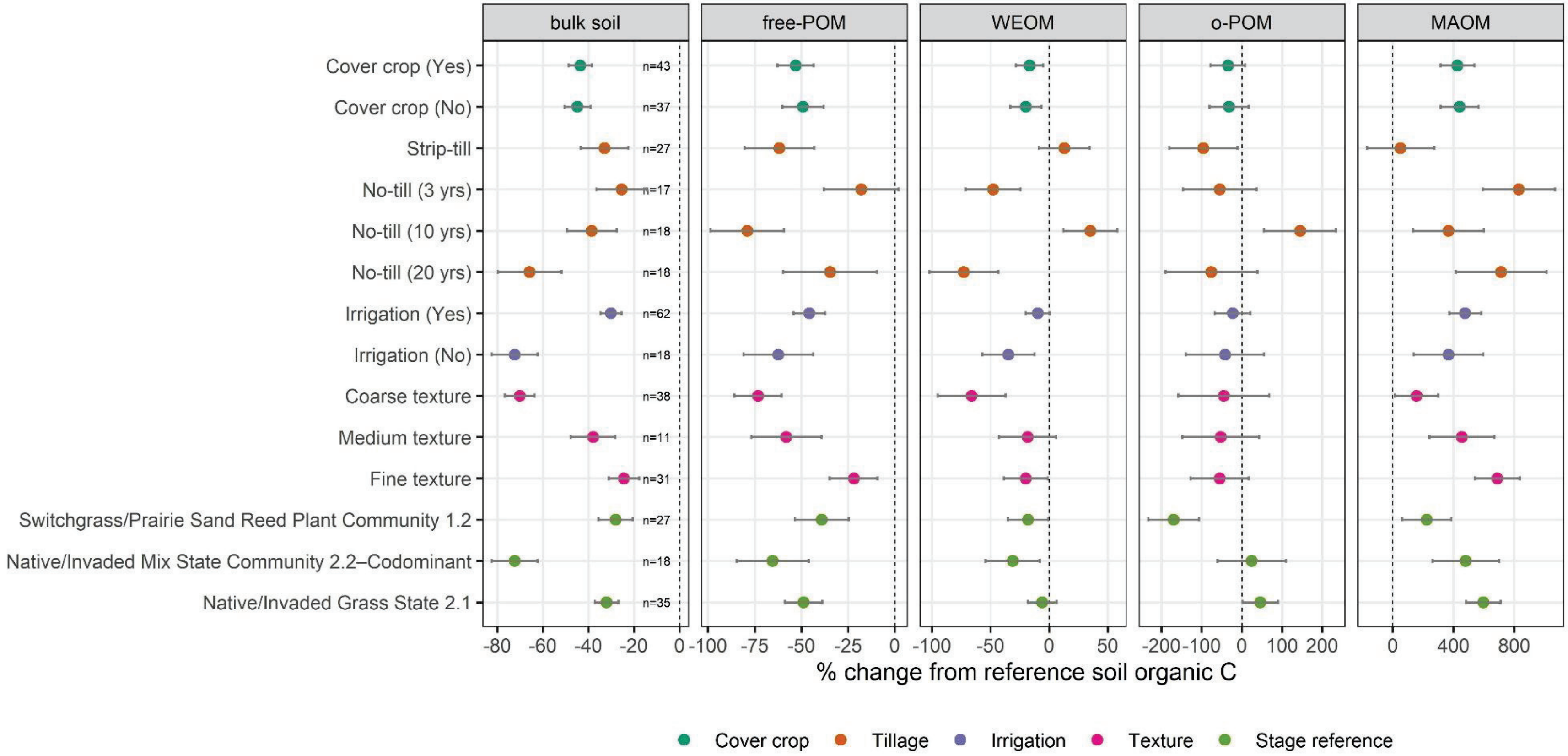

Figure 4.4. Bulk and SOM fractions mean percentage change from reference soil organic C (and 95% confidence intervals) for the factors included in the analysis: cover crop, tillage, irrigation, soil texture, and stage of reference soil. Descriptors: free-POM= free particulate organic matter, WEOM = water extractable organic matter; o-POM = aggregate occluded POM; MAOM= mineral-associated organic matter.

Effects of management, texture and reference condition on N content in bulk soil and OM fractions

The mean total soil N ranged from 0.89 and 4.37 g N kg^{-1} soil across Colfax, Greeley, Howard, and Merrick sites (Figure 4.5). Bulk soil total N content values for reference soils were 56, 30 and 22 % greater than cropland systems (both cover crop and no cover crop) in Colfax, Greeley and Merrick sites, respectively. Unlike observed for C, bulk soil total N content following cover crop adoption was comparable to values obtained for no cover crop and reference soil in Howard site. (Figure 4.4).

Within SOM fractions, N ranged from 0.19-1.25 g N kg^{-1} soil, 0.18-1.06 g N kg^{-1} soil, 0.02-0.08 g N kg^{-1} soil, and 0.38-1.51 g N kg^{-1} soil for free-POM, o-POM, WEOM, and MAOM respectively (Figure 4.5). Significant soil management effects were observed on N content across SOM fractions, but similar to C, responses were rather fraction- and site-specific (Figure 4.5). For free-POM N and WEOM N contents, reference soils increased free-POM N by 77 % (Greeley) and 66 % (Merrick) and WEOM N by 60 % (Colfax) and 41% (Merrick) compared to cropland soils (i.e., cover and no cover crop) (Figure 4.5). Similar to C, there were no differences in MAOM N content attributed to changes in soil management. Across the three soil managements tested, MAOM N content values were on average 1.08 g N kg^{-1} soil, 0.33 g N kg^{-1} soil, 1.09 g N kg^{-1} soil and 0.40 g N kg^{-1} soil for Colfax, Greeley, Howard, and Merrick sites, respectively (Figure 4.5). Similar to values observed for C, N contents of POM and WEOM were more sensitive to management changes than MAOM (Figure 4.5). Actual mean N recovery ranged from 60-80% (Figure S1). A considerably larger amount of bulk soil N was recovered in MAOM fraction (40%) and o-POM (29%) while a small amount, 2% on average, was recovered in the WEOM fraction (Figure S2). Both C and N recovery values obtained from this fractionation method (Figures S1 and S2) are in agreement with expected losses that are inevitable due to the adopted fractionation procedure (Jilling et al., 2020) and account for non-measured fractions (e.g., water-soluble fractions after ultrasonication) as observed in arable topsoils (Kaiser et al., 2010; Anuo et al., 2023).

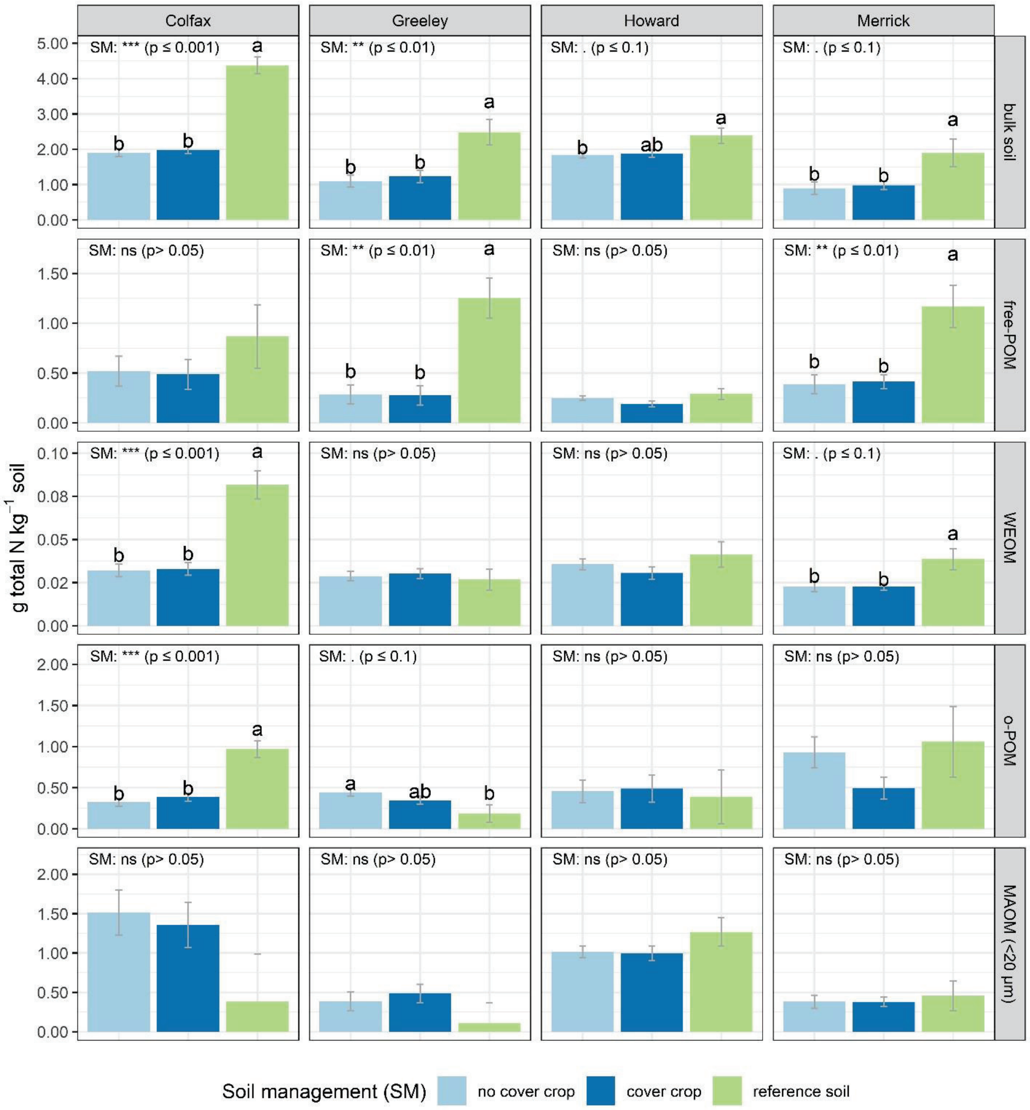

Figure 4.5. Effect of soil management on total nitrogen content across bulk soil and SOM fractions in sites located in Colfax, Greeley, Howard, and Merrick. Error bars indicate mean standard error. ANOVA results for each site and fraction provided within the respective panel with significant main effects. Bars followed by similar letters indicate no significant differences ($p < 0.1$) among soil management within each SOM fraction according to Tukey test. Descriptors: free-POM= free particulate organic matter, WEOM = water extractable organic matter; o-POM = aggregate occluded POM; MAOM= mineral-associated organic matter.

Similar to observed for C, no significant differences in soil total N between cover crop and no cover crop treatments were observed (Figure 4.5). This means that the effect of cover crops adoption on SOM N content in bulk and SOM fractions was less pronounced than the transition from cropland to grassland systems and that other factors were affecting the response (Figures 4.5 and 4.6). The highest declines in cropland bulk SOM N relative to reference soil were attributed to changes mainly in tillage and irrigation practices as well as soil edaphic characteristic, namely soil texture, and vegetation ecological dynamics of reference soils (Figure 4.6). WEOM N changes in cropland relative to reference soil were the highest in irrigated cropland and when reference condition was in Native/Invaded Grass State (Figure 4.6). Similarly, the highest increases in cropland o-POM N relative to reference soil were observed in irrigated sites adopting no-till, with coarse to medium texture and when reference condition was in Native/Invaded Grass State (Figure 4.6). MAOM N changes relative to reference soil for sites that were continuously adopting no-till for at least 10 years were higher than those for sites practicing strip-tillage or were recently (3ys) converted to no-till (Figure 4.6). In general, reference sites with vegetation in Native/Invaded Grass and Mix State Community Codominant resulted in positive changes in cropland MAOM N (Figure 4.6).

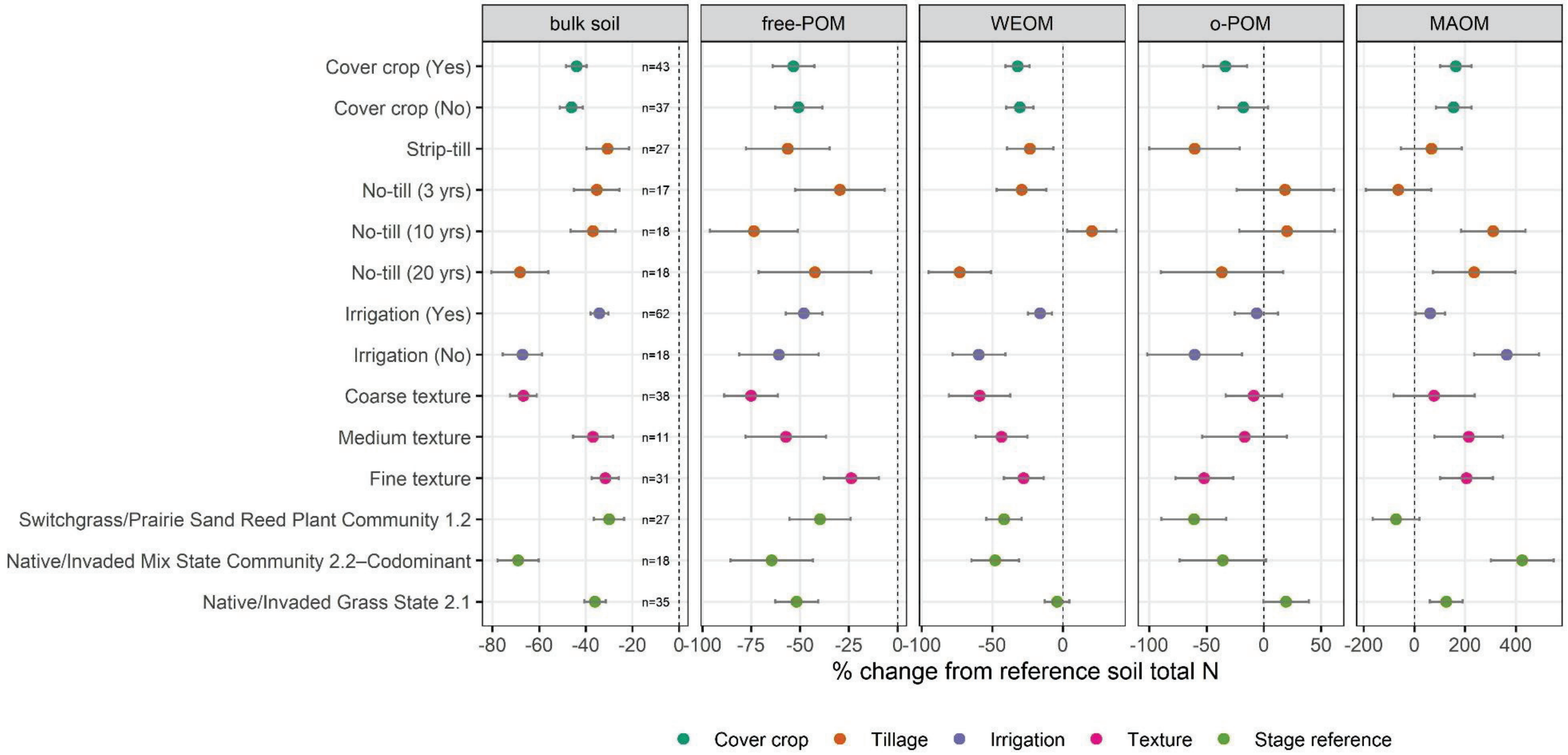

Figure 4.6. Bulk and SOM fractions mean percentage change from reference soil total N (and 95% confidence intervals) for the factors included in the analysis: cover crop, tillage, irrigation, soil texture, and stage of reference soil. Descriptors: free-POM= free particulate organic matter, WEOM = water extractable organic matter; o-POM = aggregate occluded POM; MAOM= mineral-associated organic matter.

Relationship between SOM fraction variables and other physical, chemical and biological properties

Changes in C and N content within SOM fractions were also correlated with soil physical, chemical, and biological properties (Figure 4.7). In the multivariate analysis, cover crop and no cover crop systems were clustered together but different from the reference soils cluster, indicating differences in C and N dynamics and responses to soil management, particularly the transition from cropland to grassland. The first two principal components (PC) explained 48% of the total variability. For the SOM fraction variables, C and N content of free and o-POM were positively correlated with aggregate stability, water infiltration rate, β-glucosidase enzyme activity, and soil pH as indicated by these variable's vectors pointing towards the same direction in the PCA plot (Figure 4.7). C and N content of WEOM and MAOM were, on the other hand, positively correlated with nitrate and CEC and negatively correlated with bulk density as the angle of the vectors representing these variables is either very small pointing towards the same direction (i.e., positive correlation) or in opposite direction (i.e., negative correlation).

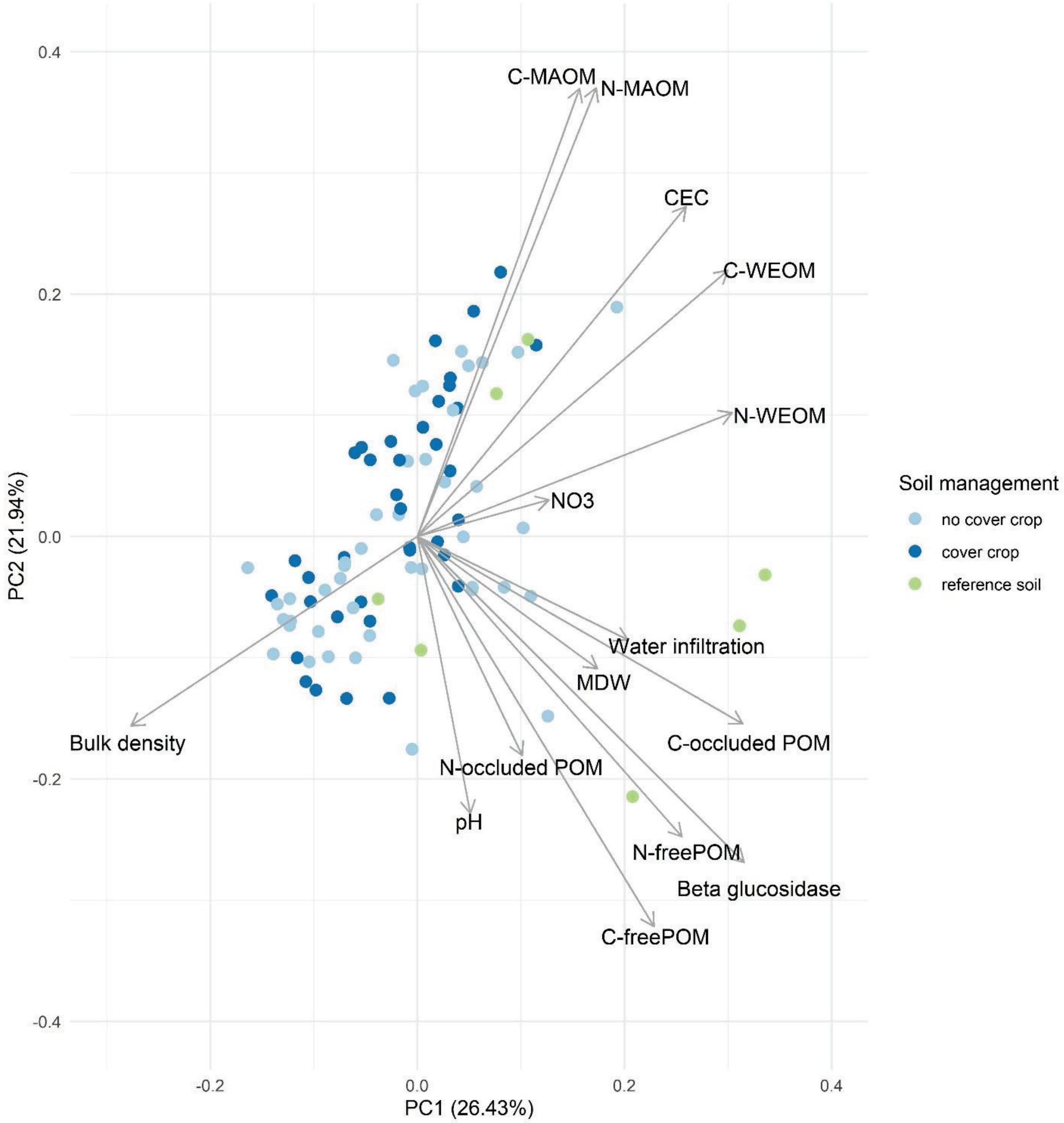

Figure 4.7. Biplot obtained from principal components analysis based on the correlation matrix, showing the two first principal components (explaining 27 % and 20 %, respectively). Each point represents samples collected, loadings indicate C and N content within SOM fractions and soil property measurements. Descriptors: CEC=cation exchange capacity, MDW= mean weight diameter of water stable aggregates, freePOM= free particulate organic matter, WEOM = water extractable organic matter; o-POM = aggregate occluded POM; MAOM= mineral-associated organic matter.

Discussion

Potential soil C sequestration of cover crop-based systems relative to reference sites is site-specific

We hypothesized that annual cropland systems integrating cover crops in the short (3-yr) term would have increased C and N stored within SOM fractions, particularly POM and WEOM, to levels higher than the no cover crop but lower than reference sites representing increased system's perenniality. Results partially corroborated our first hypothesis as changes in C and N dynamics with cover crop adoption (no cover crop vs. cover crop) and land conversion (grassland vs. cropland) were site-specific (Figure 4.4). The observed higher C content in bulk soil and free-POM, WEOM, and o-POM fractions in perennial grassland (i.e., reference soil) compared to annual cropland (both cover crop and no cover crop) (Figure 4.4) are most likely due to high plant diversity, elevated belowground C inputs (i.e., root biomass and root exudates) and decreased soil disturbances in perennial grassland (Guillaume et al., 2021; Zhang et al., 2021). This can also promote microbial growth, turnover, and entombment of necromass within clays and aggregates (Chen et al., 2018; Lange et al., 2015; Prommer et al., 2020). Across reference soils, C concentrations within WEOM, considered a precursor for MAOM formation, were the highest at Colfax and Howard sites (Figure 4.4). The highest changes in cropland WEOM C relative to reference soil observed in medium and fine compared to coarse texture soils (Figure 4.5) indicates that medium texture soils could be more easily depleted with intensive cultivation than clayey soils (Amorim et al., 2022; Hassink, 1997). Overall, the decrease in continuous living cover - plant C inputs (e.g., aboveground and belowground biomass) - coupled with tillage-induced soil disturbances due to land conversion explain our findings of reduced POM and WEOM C in cropland compared to reference soils (Liang et al., 2017; Sokol and Bradford, 2019; Villarino et al., 2021). Finally, the observed higher relative changes in WEOM and MAOM C in irrigated compared to non-irrigated cropland (Figure 4.4) is most likely a result of irrigation promoting crop-derived water-soluble leachates and ultimately increasing MAOM amount (Haddix et al., 2020) through direct association to mineral surfaces or indirect association via microbe assimilation (Kleber et al., 2015).

We expected but did not observe consistent accumulation of C across SOM fractions when transitioning from no cover crop to cover crop-based annual systems (Figure 4.4). Findings from our study seem to revisit some of the over-optimistic predictions about the potential of cover crops to affect total MAOM C (Canisares et al., 2023), which contributes to longer-term SOC sequestration in soil. Our results align with recent meta-analysis that found lack of significant MAOM C responses to cover cropping and suggest POM as the main fraction driving positive changes that may help explain the success of cover crop on SOM dynamics (Wooliver & Jagadamma, 2023). For most of the SOM fractions in our study, the cover crop-derived C is trending towards levels of reference soils (Figure 4.4), but integrating cover crop for three consecutive year-crop rotations was not enough to store SOC to levels higher than the no cover crop-based system (Figure 4.4). Recent studies documenting bulk soil C sequestration potential with increased perennialization of cropland soils, such as cover crop adoption or full conversion to permanent grassland, is relatively modest with an average value of 0.40 kg C m^2 with a 10% increase in temporary grassland globally (Guillaume at al., 2022). More specifically in US Great Plains, the estimated potential environmental footprint (e.g., net GHC and yield-scale emissions) of cover crops were comparable to no cover crop in semi-arid irrigated conditions (Acharya et al., 2022). A similar SOC response to cover crop was observed in a five-year field experiment (Anuo et al., 2023) and a literature synthesis (Blanco-Canqui, 2022), suggesting that the impacts of cover crop practices on potential soil C sequestration are site and management specific (e.g., cover crop species selection, soil properties, climate, and reference site selection). In our study, high SOM fractions C levels in systems with greater perenniality (i.e., reference conditions) but similar between cover crop and no cover crop also highlight the need for further investigation on specific cover crop management effects on soil C storage in deeper soil across different agroecoregions, climates, and soil orders (Wooliver & Jagadamma, 2023).

Our assumption that the selected reference sites represent the highest land group category to estimate cropland soil C declines and potential storage targets is questionable, particularly since reference soils consistently had MAOM C concentration values comparable to annual cropland systems (Figure 4.4). Our results of MAOM C indicate uncertainties in evaluating maximal soil organic C storage in systems with increased perenniality, which is corroborated by prior research focused on prediction models for estimation of C sequestration capacity when soils are converted from cropland to natural grassland (Chan et al., 2011; Guillaume at al., 2022). Also, despite its persistence in soils, MAOM C storage saturates and additional C storage is realized through POM accrual (Bai and Cotrufo, 2022; Cotrufo et al., 2019). Although inferences of maximum C accumulation in reference sites would require further investigations, we did observe differences in the magnitude of MAOM C content across reference sites, which was likely due to soil mineral characteristics (Figure 4.4). Both on-farm and reference sites located in Howard and Colfax counties occurred on upland Molisols with fine (i.e., more clay) surface texture that have a thick and dark surface horizons with high levels of organic C (Table 4.1). In contrast, Greeley and Merrick sites, both cropland and reference soils, occurred on Alfisols with thinner, lower carbon surface horizons compared to Molisols (Table 4.1). Overall, these results suggests that bringing soil C sequestration research to the farm scale requires careful consideration of the role of reference sites sampling approaches (Das & Maharjan, 2022). This represents critical opportunities for the scientific community to turn soil science research into evidence-based policy recommendations (e.g., financial incentive for ecosystem services for C sequestration) and for farmers to mitigate the effects of climate change and to participate in the carbon economy.

N dynamics showed higher accumulation of N-rich OM into MAOM relative to POM fractions

Our data showed that in general the N stored within free-POM and WEOM was the highest in reference soil (Figure 4.5). Also, positive changes in WEOM N relative to reference soils were observed in cropland sites under 10 years of no-till and when reference sites had vegetation community in Native/Invaded Grass State 2.1, according to state and transition models for rangeland health evaluation (Figure 4.6). This result indicates systems with increased perenniality improving the N cycling within SOM less protected against microbial decay. Given the established role WEOM plays in the translocating suspended and dissolved compounds within the soil matrix (von Luetzow, 2007), one factor that likely explains our findings is the potential of systems with increased perenniality in supplying “assimilable” sources of nutrients and energy for microorganisms (Conant et al., 2011; Lerch et al., 2011; Sanderman et al., 2008). Our results are also in agreement with a recent study assessing controlling factors driving global trends in N dynamics within SOM and reporting POM as the fraction most affected by land use type (Amorim et al., 2022). Given the partially degraded or decaying plant residues poorly protected by sorption or aggregation comprising most of the POM fraction (Cotrufo et al., 2019), our data suggest that this trend is most likely due to the combination of continuous plant biomass production year-round in grassland ecosystems (i.e., reference condition) and the faster-cycling nature of POM. Additionally, the observed shifts in N retention within POM and WEOM due to land conversion from natural to cropland systems (Figure 4.5) can reflect a decoupling of C and N cycles in soils and potential N losses (Cotrufo et al., 2021). This can limit primary production and thus the ability of agroecosystems to offset CO_2 emissions (Delgado-Baquerizo et al., 2013; Jiao et al., 2016; Wang et al., 2020).

The higher accumulation of N in MAOM relative to POM (Figure 4.5) is in agreement with observations by Amorim et al. (2022) and is most likely attributed to the accumulation of microbial-derived materials such as amino-sugars and other N-rich compounds (Guggenberger et al., 1995; Keiluweit et al., 2015; Knicker et al., 2000). Compared to free-POM, MAOM is more strongly protected against microbial decay, has a longer mean residence time in the soil, and contributes more to the stabilization of the soil structure (e.g., Poeplau et al., 2018). The observed higher changes in MAOM N in fine and medium compared to coarse soils (Figure 4.6) results most likely from the sorption of N-rich SOM to reactive clay particles (e.g., Jilling et al., 2018; Keiluweit et al., 2015) and segregation of N-poor SOM in the POM fractions (Amorim et al., 2022). This indicates that the amount of clay, or clay plus silt in soils has a significant effect on total N retention (Amorim et al., 2022) and wide implications for N cycling in terrestrial ecosystems. Even though MAOM is relatively enriched in N (Figure 4.5), inferring the availability of these N pools as a source of N for plant or microbial metabolism was beyond the scope of our study.

Our results also showed that N stored within more protected SOM fractions such as MAOM did not show responses to soil management (Figure 4.5). This was surprising given the potential of MAOM in accruing cover crop-N derived in the short-term (Jilling et al., 2020) and recycling it back during the subsequent annual crop growth (Acharya et al., 2022), all of which contributes to improved soil N cycling in cover crop-based systems. The adoption of cover crops for three consecutive years in our study also did not result in greater N retention in fast-cycling fractions such as free-POM and WEOM (Figure 4.5). Here degraded or decaying plant residues in free-POM in both cover crop and no cover crop sites were likely vulnerable to mineralization given the poor mineral protection of free-POM and the limited availability of N to satisfy microbial stoichiometric constraints (Cotrufo et al., 2013).

According to commercial soil health assessments conducted in the same on-farm sites, a minimum of eight years of continued adoption of the current cover crop management practices was required to result in substantial improvements in fertilizer N savings due to improved soil N cycling (Krupek et al., 2022a). Taken together, our results provide implications for the assessment of cover crop practices promoted in farmer's education efforts and incentive programs to optimize site-specific soil N content, forms of N retention, and N availability – all of which affect SOM cycling and storage in the soils as they limit or stimulate SOM decomposition (Averill and Waring, 2017; Cotrufo et al., 2021).

Similar to C, differences in the N distribution within SOM fractions were largely driven by soil texture (Figures 4.4 and 4.6), which corroborates findings on a global scale that demonstrate soil texture as a critical factor controlling changes in both SOM fraction C and N concentrations due to land use conversion (agriculture, forest, grassland) (Amorim et al., 2022). Given the main influence of soil texture as a site-specific factor not only in our study but also in driving C:N ratios and associated SOM quality globally (Amorim et al., 2022), our results provide implications for improvements in simulation models projecting the potential of agroecosystem C sequestration and N supply in the Northern Great Plains. Such models should take into consideration the overall influence of soil texture on soil C and N contents as well as their partition within SOM fractions.

Opportunities to integrate SOM fractions of distinct ecological function into the soil health framework

We hypothesized that more labile SOM fractions would be closely related to other soil health indicators in systems of increased perenniality. Results showed that C and N stored in free-POM and o-POM were consistently associated with aggregate stability, enzyme activity, and water infiltration rate within reference soils, which supports our second hypothesis (Figure 4.7). Similarly, we found that C and N stored within MAOM were positively associated with nutrient availability (e.g., NO_3^-) and soil's ability to hold onto essential nutrients (e.g., CEC) within cropland sites (Figure 4.7).

The strong associations between MAOM and CEC are in agreement with the findings of Oorts et al. (2003) and Skjemstad et al. (2008) showing MAOM with higher CEC than POM fractions, which contributed to greater total CEC. Although not included in the multivariate analysis, we also observed stronger associations between MAOM-C and CEC ($R^2 = 0.57$, $p < 0.001$) than between bulk SOC and CEC ($R^2 = 0.49$, $p < 0.001$), which is most likely driven by clay content (e.g., negatively charged exchange sites of clay minerals), the main predictor for CEC in soils (Kaiser et al., 2008). This supports the idea that CEC tends to increase through SOM decomposition and transformation, producing lower molecular weight SOM compounds with higher relative proportions of reactive/acidic functional groups (e.g., carboxyl, hydroxyl). Similarly, the positive associations between MAOM and nitrate availability are most likely associated with higher rates of net N mineralization from MAOM than from POM (Whalen et al., 2000). This is primarily due to the C:N ratio of MAOM being close to the stoichiometric needs of soil microbes (Mooshammer et al. 2014), which results in more mineralization from MAOM than from POM fractions. Similar findings of a strong correlation between gross N mineralization and mineral-associated and dissolved organic C were reported by Osterholz et al. (2017). Taken together, our univariate and multivariate results support the dynamic role of MAOM as both an important fraction for the long-term stabilization of N and C, and also a potential supplier of nutrients, in particular, a source of microbial and plant-available N when OM-mineral associations are weakened (Jilling et al., 2018).

Our PCA results also showed a strong association between POM fractions and aggregate stability and water infiltration, measures of soil structure, and water dynamics (Figure 4.7). Roots and hyphae are important to the formation of macro-aggregates because they create net-like structures and produce mucilage that brings soil particles and aggregates together (Six et al., 2004). As living roots and hyphae die and contribute to POM, they act as nuclei of aggregate formation (Bucka et al., 2021) through the promotion of microbial activity. The deposition of microbial byproducts and further proliferation of saprotrophic hyphae further promotes aggregate formation (Jastrow and Miller, 2018; Jastrow, 1996). Larger, less decomposed organic fragments (e.g., free-POM) can also act as catalysts in macro-aggregate formation. As mineral particles coat coarse organic particles (free-POM), promote aggregation, and increase porosity (Bucka et al., 2021; Kaiser et al., 2009), they prevent soil surface crusting and create flow paths that lead to higher infiltration rates. Lastly, considering that soil microbes are generally C-limited (Soong et al., 2018), the strong association between POM and enzyme activity in our PCA results is likely due to POM fractions providing substrates and energy to decomposers (Compton and Boone, 2002).

Implications and recommendations to optimize cover crop-based systems for improved soil C storage and N retention

Our analysis demonstrated that systems with increased perenniality improve C and N stored within SOM fractions, but changes resulting from current cover crop practices are less pronounced in the short (3-yrs) term (Figures 4.3, 4.4, 4.5 and 4.6). The lack of significant differences between cover crop and no cover crop systems in C and N content of most of the SOM fractions, but specifically in free and o-POM, could be a result of low cover crop biomass accumulation (0.16 – 3.0 Mg ha^{-1}) (Table 4.1). The short implementation time of cover crops and reduced tillage practices at some of the on-farm sites might be another reason (Table 4.1). Cover crop above and below-ground biomass production can be relatively low in our growing region (Ruis et al., 2019, 2020). According to Blanco-Canqui (2022), a significant SOC accumulation (0.2–0.92 Mg C ha^{-1} yr^{-1}) results from cover crop aboveground biomass production greater than 2 Mg ha^{-1}, when integrated more than 5 yrs. Tillage and irrigation practices also affect SOM dynamics (Figures 4.4 and 4.6). Reduced soil disturbance or disruption of soil aggregate, through long-term continuous no-till, is important to increase the amount of aggregate protected C and N and ultimately promote MAOM accumulation (Fulton-Smith and Cotrufo, 2019; Kravchenko et al., 2019). Thus, the lack of consistent increases in C and N content within SOM fractions from integrating cover crops in corn-soybean rotations is less surprising, given the differences in tillage and irrigation practices performed by farmer collaborators, low cover crop aboveground biomass, and short time of cover crop implementation before soil sampling (Table 4.1).

Thus, our results lend information toward efforts and incentive programs in the study region as they assess to potential for cover crop management (e.g., planting/termination dates, seeding rate, and methods, and species selection) to improve C and N cycling (Blanco-Canqui, 2022; Guillaume et al., 2022; McClelland et al., 2021). To the extent that this collaboratively designed on-farm research provided farmers with an improved understanding of the benefits of more environmentally sound agronomic management practices that promote continuous living cover in cropping systems, experience with cover crops could translate into improved sink of C and N in the long run as farmers are better able to adapt management practices to individual farming operations. Extending cover crop growing window through early planting and late termination dates coupled with shorter-season annual crop management adaptations (Chatterjee et al., 2020; Sciarresi et al., 2020), particularly when adopted in eroded and marginal lands that are furthest from the maximum mineralogical capacity, might be an option for higher accrual C and N rates (Craig et al., 2021; Georgiou et al., 2022; Lorenz and Lal, 2005) than the conditions studied here.

Conclusions

The overall trend quantified by this analysis is the potential of systems with increased perenniality to improve C and N stored within SOM fractions, but with a less pronounced cover crop effect observed in the short (3-yrs) term, and under reduced-tillage, non-irrigated, and low biomass-producing systems (< 3 Mg biomass ha^{-1}). Another important finding is that operationally defined SOM fractions were related to soil properties representing functions such as water infiltration, nutrient retention, erosion control, and belowground biodiversity. This demonstrates the potential to integrate specific SOM fractions into soil health assessments.

Although the findings from our study seem to revisit some of the over-optimistic predictions regarding the potential of cover crop-based systems to mitigate climate change and improve long-term soil fertility, they also highlight the importance of agroecosystems systems with greater perenniality as a strategy to maintain or enhance ecosystem services and capabilities to adapt to climate change.

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References

Abiven, S., Menasseri, S., Angers, D. A., Leterme, P., 2007. Dynamics of aggregate stability and biological binding agents during decomposition of organic materials. Eur. J. Soil Sci. 58(1), 239-247. https://doi.org/10.1111/j.1365-2389.2006.00833.x

Acharya, P., Ghimire, R., Paye, W. S., Ganguli, A. C., DelGrosso, S. J., 2022. Net greenhouse gas balance with cover crops in semi-arid irrigated cropping systems. Sci. Rep. 12(1), 1-13. https://doi.org/10.1038/s41598-022-16719-w

Amelung, W., Zech, W., 1999. Minimisation of organic matter disruption during particle-size fractionation of grassland epipedons. Geoderma. 92(1-2), 73-85. https://doi.org/10.1016/S0016-7061(99)00023-3

Amorim, H. C., Hurtarte, L. C., Souza, I. F., Zinn, Y. L., 2022. C: N ratios of bulk soils and particle-size fractions: Global trends and major drivers. Geoderma. 425, 116026. https://doi.org/10.1016/j.geoderma.2022.116026

Anuo, C. O., Cooper, J. A., Koehler-Cole, K., Ramirez II, S., & Kaiser, M. (2023). Effect of cover cropping on soil organic matter characteristics: Insights from a five-year field experiment in Nebraska. *Agriculture, Ecosystems & Environment*, *347*, 108393.

Austin, E. E., Wickings, K., McDaniel, M. D., Robertson, G. P., Grandy, A. S., 2017. Cover crop root contributions to soil carbon in a no-till corn bioenergy cropping system. Gcb Bioenergy. 9(7), 1252-1263. https://doi.org/10.1111/gcbb.12428

Averill, C., Waring, B., 2018. Nitrogen limitation of decomposition and decay: How can it occur?. Glob. Change Biol. 24(4), 1417-1427. https://doi.org/10.1111/gcb.13980

Bai, Y., Cotrufo, M. F., 2022. Grassland soil carbon sequestration: Current understanding, challenges, and solutions. Science. 377(6606), 603-608. https://doi.org/10.1126/science.abo2380

Bardgett, R. D., Bullock, J. M., Lavorel, S., Manning, P., Schaffner, U., Ostle, N., ... & Shi, H., 2021. Combatting global grassland degradation. Nat. Rev. Earth & Environ. 2(10), 720-735. https://doi.org/10.1038/s43017-021-00207-2

Basche, A. D., Edelson, O. F., 2017. Improving water resilience with more perennially based agriculture. Agroecol. Sust. Food. 41(7), 799-824. https://doi.org/10.1080/21683565.2017.1330795

Bertora, C., Cucu, M. A., Lerda, C., Peyron, M., Bardi, L., Gorra, R., ... & Said-Pullicino, D., 2018. Dissolved organic carbon cycling, methane emissions and related microbial populations in temperate rice paddies with contrasting straw and water management. Agric. Ecosyst. Environ. 265, 292-306. https://doi.org/10.1016/j.agee.2018.06.004

Bestelmeyer, B. T., Ash, A., Brown, J. R., Densambuu, B., Fernández- Giménez, M., Johanson, J., Levi, M., Lopez, D., Peinetti, R., Rumpff, L., Shaver, P., 2017. State and transition models: Theory, applications, and challenges. In Rangeland systems (pp. 303–345). Springer.

Bhattacharyya, R., Tuti, M. D., Kundu, S., Bisht, J. K., Bhatt, J. C., 2012. Conservation tillage impacts on soil aggregation and carbon pools in a sandy clay loam soil of the Indian Himalayas. Soil Sci. Soc. Am. J. 76(2), 617-627. https://doi.org/10.2136/sssaj2011.0320

Blake, G., Hartge, K., 1986. Bulk density, in: Klute, A. (Ed.), Methods of soil analysis. Part 1. Physical and mineralogical methods. Madison, WI: ASA and SSSA, pp. 363–375.

Blanco-Canqui, H., 2022. Cover crops and carbon sequestration: Lessons from US studies. Soil Sci. Soc. Am. J. 86(3), 501-519. https://doi.org/10.1002/saj2.20378

Bowman, M., & Lynch, L., 2019. Government programs that support farmer adoption of soil health practices. Choices, 34(2), 1-8. https://www.jstor.org/stable/26785777 (accessed 2 December 2022).

Bowman, M., Poley, K., McFarland, E., 2022. Farmers employ diverse cover crop management strategies to meet soil health goals. Agr. Env. Lett. *7*(1), e20070. https://doi.org/10.1002/ael2.20070

Bu, R., Ren, T., Lei, M., Liu, B., Li, X., Cong, R., ... & Lu, J., 2020. Tillage and straw-returning practices effect on soil dissolved organic matter, aggregate fraction and bacteria community under rice-rice-rapeseed rotation system. Agric. Ecosyst. Environ. 287, 106681. https://doi.org/10.1016/j.agee.2019.106681

Buck, H. J., Palumbo-Compton, A., 2022. Soil carbon sequestration as a climate strategy: what do farmers think?. Biogeochemistry, 1-12. https://doi.org/10.1007/s10533-022-00948-2

Bucka, F. B., Felde, V. J., Peth, S., Kögel-Knabner, I., 2021. Disentangling the effects of OM quality and soil texture on microbially mediated structure formation in artificial model soils. Geoderma, 403, 115213. https://doi.org/10.1016/j.geoderma.2021.115213

Canisares, L. P., Banet, T., Rinehart, B., McNear, D., & Poffenbarger, H., 2023. Litter quality and living roots affected the formation of new mineral-associated organic carbon but did not affect total mineral-associated organic carbon in a short-term incubation. Geoderma, 430, 116302. https://doi.org/10.1016/j.geoderma.2022.116302

Chan, K. Y., Heenan, D. P., Oates, A., 2002. Soil carbon fractions and relationship to soil quality under different tillage and stubble management. Soil Till. Res. 63(3-4), 133-139. https://doi.org/10.1016/S0167-1987(01)00239-2

Chan, K.Y., Conyers, M.K., Li, G.D., Helyar, K.R., Poile, G., Oates, A., Barchia, I.M., 2011. Soil carbon dynamics under different cropping and pasture management in temperate Australia: Results of three long-term experiments. Soil Res. 49 (4), 320–328. https://doi.org/10.1071/SR10185.

Chantigny, M. H., 2003. Dissolved and water-extractable organic matter in soils: a review on the influence of land use and management practices. Geoderma, 113(3-4), 357-380. https://doi.org/10.1016/S0016-7061(02)00370-1

Chatterjee, N., Archontoulis, S. V., Bastidas, A., Proctor, C. A., Elmore, R. W., & Basche, A. D., 2020. Simulating winter rye cover crop production under alternative management in a corn-soybean rotation. Agron. J. 112(6), 4648-4665. https://doi.org/10.1002/agj2.20377

Chen, J., Xiao, W., Zheng, C., Zhu, B., 2020. Nitrogen addition has contrasting effects on particulate and mineral-associated soil organic carbon in a subtropical forest. Soil Biol. Biochem. 142, 107708. https://doi.org/10.1016/j.soilbio.2020.107708

Chen, S., Wang, W., Xu, W., Wang, Y., Wan, H., Chen, D., ... & Bai, Y., 2018. Plant diversity enhances productivity and soil carbon storage. Proc. Natl. Acad. Sci. 115(16), 4027-4032. https://doi.org/10.1073/pnas.170029811

Chivenge, P. P., Murwira, H. K., Giller, K. E., Mapfumo, P., Six, J., 2007. Long-term impact of reduced tillage and residue management on soil carbon stabilization: Implications for conservation agriculture on contrasting soils. Soil Till. Res. 94(2), 328-337. https://doi.org/10.1016/j.still.2006.08.006

Christensen, B. T., 2001. Physical fractionation of soil and structural and functional complexity in organic matter turnover. Eur. J. Soil Sci. 52(3), 345-353. https://doi.org/ 10.1046/j.1365-2389.2001.00417.x.

Compton, J. E., Boone, R. D., 2002. Soil nitrogen transformations and the role of light fraction organic matter in forest soils. Soil Biol. Biochem. 34(7), 933-943. https://doi.org/10.1016/S0038-0717(02)00025-1

Conant, R. T., Cerri, C. E., Osborne, B. B., Paustian, K., 2017. Grassland management impacts on soil carbon stocks: a new synthesis. Ecol Appl. 27(2), 662-668. https://doi.org/10.1002/eap.1473

Conant, R.T., Ryan, M. G., Ågren, G. I., Birge, H. E., Davidson, E. A., Eliasson, P. E., Bradford, M. A., 2011. Temperature and soil organic matter decomposition rates-Synthesis of current knowledge and a way forward. Global Change Biology, 17, 3392–3404. https://doi.org/10.1111/j.1365-2486.2011.02496.x

Cotrufo, F. M., Lavallee, J. M., Zhang, Y., Hansen, P. M., Paustian, K. H., Schipanski, M., & Wallenstein, M. D., 2021. I n-N-O ut: A hierarchical framework to understand and predict soil carbon storage and nitrogen recycling. Glob Chang Biol. 27(19).

Cotrufo, M. F., Lavallee, J. M., 2022. Soil organic matter formation, persistence, and functioning: A synthesis of current understanding to inform its conservation and regeneration. In: Sparks, D. L. (Eds.), Advances in Agronomy. Academic Press, Cambridge, pp. 1-66. https://doi.org/10.1016/bs.agron.2021.11.002

Cotrufo, M. F., Ranalli, M. G., Haddix, M. L., Six, J., & Lugato, E., 2019. Soil carbon storage informed by particulate and mineral-associated organic matter. Nat. Geosci. 12(12), 989-994. https://doi.org/10.1038/s41561-019-0484-6

Cotrufo, M. F., Soong, J. L., Horton, A. J., Campbell, E. E., Haddix, M. L., Wall, D. H., Parton, W. J., 2015. Formation of soil organic matter via biochemical and physical pathways of litter mass loss. Nat. Geosci. 8(10), 776-779. https://doi.org/10.1038/ngeo2520

Cotrufo, M. F., Wallenstein, M. D., Boot, C. M., Denef, K., & Paul, E., 2013. The M icrobial E fficiency-M atrix S tabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter?. Glob Chang Biol. 19(4), 988-995. https://doi.org/10.1111/gcb.12113

Craig, M. E., Mayes, M. A., Sulman, B. N., Walker, A. P., 2021. Biological mechanisms may contribute to soil carbon saturation patterns. Glob Chang Biol. 27(12), 2633-2644. https://doi.org/10.1111/gcb.15584

Daly, A. B., Jilling, A., Bowles, T. M., Buchkowski, R. W., Frey, S. D., Kallenbach, C. M., ... & Grandy, A. S., 2021. A holistic framework integrating plant-microbe-mineral regulation of soil bioavailable nitrogen. Biogeochemistry, 1-19. https://doi.org/10.1007/s10533-021-00793-9

Das, S., & Maharjan, B., 2022. Cropland Reference Ecological Unit: A land classification unit for comparative soil studies. Ecological Indicators, 144, 109468. https://doi.org/10.1016/j.ecolind.2022.109468

Delgado-Baquerizo, M., Maestre, F. T., Gallardo, A., Bowker, M. A., Wallenstein, M. D., Quero, J. L., ... & Zaady, E., 2013. Decoupling of soil nutrient cycles as a function of aridity in global drylands. Nature, 502(7473), 672-676.

Denef, K., Del Galdo, I., Venturi, A., Cotrufo, M. F., 2013. Assessment of soil C and N stocks and fractions across 11 European soils under varying land uses. Open J. Soil Sci. 3(7), 297-313. 10.4236/ojss.2013.37035

Duval, M.E., Galantini, J.A., Capurro, J.E., Martinez, J.M., 2016. Winter cover crops in soybean monoculture: effects on soil organic carbon and its fractions. Soil Tillage Res. 161, 95–105. https://doi.org/10.1016/J.STILL.2016.04.006.

Fleming, A., Stitzlein, C., Jakku, E., Fielke, S., 2019. Missed opportunity? Framing actions around co-benefits for carbon mitigation in Australian agriculture. Land use policy, 85, 230-238. https://doi.org/10.1016/j.landusepol.2019.03.050

Frank, S., Havlík, P., Stehfest, E., van Meijl, H., Witzke, P., Pérez-Domínguez, I., ... & Valin, H., 2019. Agricultural non-CO2 emission reduction potential in the context of the 1.5° C target. Nat. Clim. Change. 9(1), 66-72. https://doi.org/10.1038/s41558-018-0358-8

Fulton-Smith, S., Cotrufo, M. F., 2019. Pathways of soil organic matter formation from above and belowground inputs in a Sorghum bicolor bioenergy crop. GCB Bioenergy, 11(8), 971-987. https://doi.org/10.1111/gcbb.12598

Gartzia-Bengoetxea, N., Gonzalez-Arias, A., Merino, A., de Arano, I. M., 2009. Soil organic matter in soil physical fractions in adjacent semi-natural and cultivated stands in temperate Atlantic forests. Soil Biol. Biochem. 41(8), 1674-1683. https://doi.org/10.1016/j.soilbio.2009.05.010

Gee, G. W. & Bauder, J. W. (1986). Particle-size analysis, in: Klute A. (Ed.), Methods of soil analysis Part 1. Physical and mineralogical methods (pp. 383–399). Amer. Soc. Agron., Madison, WI. https://doi.org/10.2136/sssabookser5.1.2ed.c15

Georgiou, K., Jackson, R. B., Vindušková, O., Abramoff, R. Z., Ahlström, A., Feng, W., ... & Torn, M. S., 2022. Global stocks and capacity of mineral-associated soil organic carbon. Nat. Commun. 13(1), 1-12. https://doi.org/10.1038/s41467-022-31540-9

Grandy, A. S., Neff, J. C., 2008. Molecular C dynamics downstream: the biochemical decomposition sequence and its impact on soil organic matter structure and function. Sci. Total Environ. 404(2-3), 297-307. https://doi.org/10.1016/j.scitotenv.2007.11.013

Gravuer, K., Gennet, S., Throop, H. L., 2019. Organic amendment additions to rangelands: A meta-analysis of multiple ecosystem outcomes. Glob Chang Biol. 25(3), 1152-1170. https://doi.org/10.1111/gcb.14535

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., ... & Fargione, J., 2017. Natural climate solutions. Proc. Natl. Acad. Sci. 114(44), 11645-11650. https://doi.org/10.1073/pnas.1710465114

Gross, A., Bromm, T., Glaser, B., 2021. Soil organic carbon sequestration after biochar application: A global meta-analysis. Agronomy, 11(12), 2474. https://doi.org/10.3390/agronomy11122474

Guardia, G., Aguilera, E., Vallejo, A., Sanz-Cobena, A., Alonso-Ayuso, M., Quemada, M., 2019. Effective climate change mitigation through cover cropping and integrated fertilization: A global warming potential assessment from a 10-year field experiment. J Clean. Prod. 241, 118307. https://doi.org/10.1016/j.jclepro.2019.118307

Guggenberger, G., Zech, W., Haumaier, L., Christensen, B. T., 1995. Land-use effects on the composition of organic matter in particle-size separates of soils: II. CPMAS and solution 13C NMR analysis. Eur. J. Soil Sci. 46(1), 147-158. https://doi.org/10.1111/j.1365-2389.1995.tb01821.x

Guillaume, T., Bragazza, L., Levasseur, C., Libohova, Z., & Sinaj, S. (2021). Long-term soil organic carbon dynamics in temperate cropland-grassland systems. Agriculture, Ecosystems & Environment, 305, 107184. https://doi.org/10.1016/j.agee.2020.107184

Guillaume, T., Makowski, D., Libohova, Z., Elfouki, S., Fontana, M., Leifeld, J., ... & Sinaj, S., 2022. Carbon storage in agricultural topsoils and subsoils is promoted by including temporary grasslands into the crop rotation. Geoderma, 422, 115937. https://doi.org/10.1016/j.geoderma.2022.115937

Guo, L. J., Zhang, Z. S., Wang, D. D., Li, C. F., Cao, C. G., 2015. Effects of short-term conservation management practices on soil organic carbon fractions and microbial community composition under a rice-wheat rotation system. Biol. Fertil. Soils. 51(1), 65-75. https://doi.org/10.1007/s00374-014-0951-6

Gutknecht, J., Journey, A., Peterson, H., Blair, H., Cates, A., 2022. Cover crop management practices to promote soil health and climate adaptation: Grappling with varied success from farmer and researcher observations. J. Environ. Qual. https://doi.org/10.1002/jeq2.20383

Haddix, M. L., Gregorich, E. G., Helgason, B. L., Janzen, H., Ellert, B. H., Cotrufo, M. F., 2020. Climate, carbon content, and soil texture control the independent formation and persistence of particulate and mineral-associated organic matter in soil. Geoderma, 363, 114160. https://doi.org/10.1016/j.geoderma.2019.114160

Haddix, M. L., Paul, E. A., Cotrufo, M. F., 2016. Dual, differential isotope labeling shows the preferential movement of labile plant constituents into mineral-bonded soil organic matter. Glob Chang Biol. 22(6), 2301-2312. https://doi.org/10.1111/gcb.13237

Hassink, J., 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. Plant soil. 191(1), 77-87. https://doi.org/10.1023/A: 1004213929699

Hatton, P. J., Kleber, M., Zeller, B., Moni, C., Plante, A. F., Townsend, K., ... & Derrien, D., 2012. Transfer of litter-derived N to soil mineral–organic associations: evidence from decadal 15N tracer experiments. Org. Geochem. 42(12), 1489-1501. https://doi.org/10.1016/j.orggeochem.2011.05.002

Jastrow, J. D., 1996. Soil aggregate formation and the accrual of particulate and mineral-associated organic matter. Soil Biol. Biochem. 28(4-5), 665-676. https://doi.org/10.1016/0038-0717(95)00159-X

Jastrow, J. D., Miller, R. M., 2018. Soil aggregate stabilization and carbon sequestration: feedbacks through organomineral associations. In Soil processes and the carbon cycle (pp. 207-223). CRC press.

Jiao, F., Shi, X. R., Han, F. P., Yuan, Z. Y., 2016. Increasing aridity, temperature and soil pH induce soil CNP imbalance in grasslands. Sci. Rep. 6(1), 1-9. https://doi.org/10.1038/srep19601

Jilling, A., Kane, D., Williams, A., Yannarell, A. C., Davis, A., Jordan, N. R., ... & Grandy, A. S., 2020. Rapid and distinct responses of particulate and mineral-associated organic nitrogen to conservation tillage and cover crops. Geoderma, 359, 114001. https://doi.org/10.1016/j.geoderma.2019.114001

Jilling, A., Keiluweit, M., Contosta, A. R., Frey, S., Schimel, J., Schnecker, J., ... & Grandy, A. S., 2018. Minerals in the rhizosphere: overlooked mediators of soil nitrogen availability to plants and microbes. Biogeochemistry, 139(2), 103-122. https://doi.org/10.1007/s10533-018-0459-5

Kaiser, M., Asefaw Berhe, A., 2014. How does sonication affect the mineral and organic constituents of soil aggregates?—A review. J. Soil Sci. Plant Nutr. 177(4), 479-495. https://doi.org/10.1002/jpln.201300339

Kaiser, M., Ellerbrock, R. H., & Gerke, H. H., 2008. Cation exchange capacity and composition of soluble soil organic matter fractions. Soil Sci. Soc. Am. J. 72(5), 1278-1285. https://doi.org/10.2136/sssaj2007.0340

Kaiser, M., Ellerbrock, R. H., Sommer, M., 2009. Separation of coarse organic particles from bulk surface soil samples by electrostatic attraction. Soil Sci. Soc. Am. J. 73(6), 2118-2130. https://doi.org/10.2136/sssaj2009.0046

Kaiser, M., Wirth, S., Ellerbrock, R. H., Sommer, M., 2010. Microbial respiration activities related to sequentially separated, particulate and water-soluble organic matter fractions from arable and forest topsoils. Soil Biol. Biochem. 42(3), 418-428. https://doi.org/10.1016/j.soilbio.2009.11.018

Kallenbach, C. M., Frey, S. D., Grandy, A. S., 2016. Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. Nat. Commun. 7(1), 1-10. https://doi.org/10.1038/ncomms13630

Kaye, J. P., Quemada, M., 2017. Using cover crops to mitigate and adapt to climate change. A review. Agron. Sustain. Dev. 37(1), 1-17. https://doi.org/10.1007/s13593-016-0410-x

Keeney, D.R. Nelson, D. W., 1982. Nitrogen-inorganic forms. In Page, A.L., R.H. Miller and D.R. Keeney (Eds.) Methods of Soil Analysis. Part 2 – Chemical and microbiological properties. (2nd edition). Agronomy 9:643-698. https://doi.org/10.2134/agronmonogr9.2.2ed.c33

Keiluweit, M., Bougoure, J. J., Nico, P. S., Pett-Ridge, J., Weber, P. K., Kleber, M., 2015. Mineral protection of soil carbon counteracted by root exudates. Nat. Clim. Change. 5(6), 588-595. https://doi.org/10.1038/NCLIMATE2580

Kleber, M., Eusterhues, K., Keiluweit, M., Mikutta, C., Mikutta, R., Nico, P. S., 2015. Mineral–organic associations: formation, properties, and relevance in soil environments. In Advances in agronomy (Vol. 130, pp. 1-140). Academic Press.

Knicker, H., 2011. Soil organic N-An under-rated player for C sequestration in soils?. Soil Biol. Biochem. 43(6), 1118-1129. https://doi.org/10.1016/j.soilbio.2011.02.020

Knicker, H., Schmidt, M. W., KoÈgel-Knabner, I., 2000. Nature of organic nitrogen in fine particle size separates of sandy soils of highly industrialized areas as revealed by NMR spectroscopy. Soil Biol. Biochem. 32(2), 241-252. https://doi.org/10.1016/ S0038-0717(99)00154-6

Koehler-Cole, K., Elmore, R.W., Blanco-Canqui, H., Francis, C.A., Shapiro, C.A., Proctor, C.A., Ruis, S.J., Heeren, D.M., Irmak, S., Ferguson, R.B., 2020. Cover crop productivity and subsequent soybean yield in the western Corn Belt. Agron. J. 112, 2649–2663. https://doi.org/10.1002/agj2.20232.

Kravchenko, A. N., Guber, A. K., Razavi, B. S., Koestel, J., Quigley, M. Y., Robertson, G. P., Kuzyakov, Y., 2019. Microbial spatial footprint as a driver of soil carbon stabilization. Nat. Commun. 10(1), 1-10. https://doi.org/10.1038/s41467-019-11057-4

Krupek, F. S., Mizero, S. M., Redfearn, D., & Basche, A., 2022b. Assessing how cover crops close the soil health gap in on-farm experiments. Agric. Environ. Lett. e20088. https://doi.org/10.1002/ael2.20088

Krupek, F. S., Redfearn, D., Eskridge, K. M., Basche, A., 2022a. Ecological intensification with soil health practices demonstrates positive impacts on multiple soil properties: A large-scale farmer-led experiment. Geoderma, 409, 115594. https://doi.org/10.1016/j.geoderma.2021.115594.

Lal, R., 2020. Soil organic matter and water retention. Agron J. 112(5), 3265-3277. https://doi.org/10.1002/agj2.20282

Lange, M., Eisenhauer, N., Sierra, C. A., Bessler, H., Engels, C., Griffiths, R. I., ... & Gleixner, G., 2015. Plant diversity increases soil microbial activity and soil carbon storage. Nat. Commun. 6(1), 1-8. https://doi.org/10.1038/ncomms7707

Lavallee, J. M., Soong, J. L., Cotrufo, M. F., 2020. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. Glob. Change Biol. 26(1), 261-273. https://doi.org/10.1111/gcb.14859

Lehmann, J., Kleber, M., 2015. The contentious nature of soil organic matter. Nature, 528(7580), 60-68. https://doi.org/10.1038/nature16069

Lerch, T.Z., Nunan, N., Dignac, M.F., Chenu, C., Mariotti, A., 2011. Variations in microbial isotopic fractionation during soil organic matter decomposition. Biogeochemistry*,* 106, 5-21. https://www.jstor.org/stable/41490503

Liang, C., Schimel, J. P., Jastrow, J. D., 2017. The importance of anabolism in microbial control over soil carbon storage. Nat. Microbiol. 2(8), 1-6. https://doi.org/10.1038/nmicrobiol.2017.105

Lorenz, K., Lal, R., 2005. The depth distribution of soil organic carbon in relation to land use and management and the potential of carbon sequestration in subsoil horizons. Adv. Agron. 88, 35-66. https://doi.org/10.1016/S0065-2113(05)88002-2

Lugato, E., Lavallee, J. M., Haddix, M. L., Panagos, P., Cotrufo, M. F., 2021. Different climate sensitivity of particulate and mineral-associated soil organic matter. Nat. Geosci. 14(5), 295-300. https://doi.org/10.1038/s41561-021-00744-x

Maharjan, B., Das, S., 2021. Reference Ecological Unit: A Land Classification Unit for Comparative Soil Studies. Earth Space Sci. Open Archive (ESSOAr). https://doi.org/10.1002/essoar.10508283.1

Maharjan, B., Das, S., Acharya, B. S., 2020. Soil Health Gap: A concept to establish a benchmark for soil health management. Glob. Ecol. Conserv. 23, e01116. https://doi.org/10.1016/j.gecco.2020.e01116

McClelland, S. C., Paustian, K., Schipanski, M. E., 2021. Management of cover crops in temperate climates influences soil organic carbon stocks: a meta-analysis. Ecol Appl. 31(3), e02278. https://doi.org/10.1002/eap.2278

Miltner, A., Bombach, P., Schmidt-Brücken, B., Kästner, M., 2012. SOM genesis: microbial biomass as a significant source. Biogeochemistry, 111(1), 41-55. https://doi.org/10.1007/s10533-011-9658-z

Mooshammer, M., Wanek, W., Zechmeister-Boltenstern, S., Richter, A. A., 2014. Stoichiometric imbalances between terrestrial decomposer communities and their resources: mechanisms and implications of microbial adaptations to their resources. Front. Microbiol. 22. https://doi.org/10.3389/fmicb.2014.00022

Mosier, S., Apfelbaum, S., Byck, P., Calderon, F., Teague, R., Thompson, R., Cotrufo, M. F., 2021. Adaptive multi-paddock grazing enhances soil carbon and nitrogen stocks and stabilization through mineral association in southeastern US grazing lands. J. Environ. Manage. 288, 112409. https://doi.org/10.1016/j.jenvman.2021.112409

Munkholm, L. J., Heck, R. J., Deen, B., Zidar, T., 2016. Relationship between soil aggregate strength, shape and porosity for soils under different long-term management. Geoderma, 268, 52-59. https://doi.org/10.1016/j.geoderma.2016.01.005

Nebraska Extension On-Farm Research, 2021. Cover crop studies. In 2021 on-farm research results (pp. 142–182). https://on-farm-research.unl.edu/pdfs/research/result-publications/2021research-results.pdf

Nimmo, J.R., Perkins, K.S., 2002. Aggregate stability and size distribution. In: J.H. Dane, and G.C. Topp, editors, Methods of soil analysis. *Part 4*. SSSA Book Ser. 5. SSSA, Madison, WI. p. 317– 327.

Oorts, K., Vanlauwe, B., Merckx, R., 2003. Cation exchange capacities of soil organic matter fractions in a Ferric Lixisol with different organic matter inputs. Agric. Ecosyst. Environ. 100(2-3), 161-171. https://doi.org/10.1016/S0167-8809(03)00190-7

Osterholz, W. R., Rinot, O., Shaviv, A., Linker, R., Liebman, M., Sanford, G., ... & Castellano, M. J., 2017. Predicting gross nitrogen mineralization and potentially mineralizable nitrogen using soil organic matter properties. Soil Sci. Soc. Am. J. 81(5), 1115-1126. https://doi.org/10.2136/sssaj2017.02.0055

Poeplau, C., Don, A., 2015. Carbon sequestration in agricultural soils via cultivation of cover crops–A meta-analysis. Agric. Ecosyst. Environ. 200, 33-41. https://doi.org/10.1016/j.agee.2014.10.024

Poeplau, C., Don, A., Six, J., Kaiser, M., Benbi, D., Chenu, C., Nieder, R., 2018. Isolating organic carbon fractions with varying turnover rates in temperate agricultural soils –A comprehensive method comparison. Soil Biol. Biochem. 125, 10–26. https://doi.org/10.1016/j.soilbio.2018.06.025

Prokopy, L. S., Gramig, B. M., Bower, A., Church, S. P., Ellison, B., Gassman, P. W., ... & Ulrich-Schad, J. D., 2020. The urgency of transforming the Midwestern US landscape into more than corn and soybean. Agric. Human Values. 37, 537-539. https://doi.org/10.1007/s10460-020-10077-x

Prommer, J., Walker, T. W., Wanek, W., Braun, J., Zezula, D., Hu, Y., ... & Richter, A., 2020. Increased microbial growth, biomass, and turnover drive soil organic carbon accumulation at higher plant diversity. Glob. Change Biol. 26(2), 669-681. https://doi.org/10.1111/gcb.14777

R Core Team, 2018. R: A language and environment for statistical computing. https:// www.R-project.org/ (accessed 2 March 2021).

Rabbi, S. M. F., Daniel, H., Lockwood, P. V., Macdonald, C., Pereg, L., Tighe, M., ... & Young, I. M., 2016. Physical soil architectural traits are functionally linked to carbon decomposition and bacterial diversity. Sci. Rep. 6(1), 1-9. https://doi.org/10.1038/srep33012

Rakkar, M. K., Blanco-Canqui, H., Rasby, R. J., Ulmer, K., Cox-O'Neill, J., Drewnoski, M. E., ... & MacDonald, J. C., 2019. Grazing Crop Residues Has Less Impact in the Short-Term on Soil Properties than Baling in the Central Great Plains. Agron J. 111(1), 109-121. https://doi.org/10.2134/agronj2018.03.0224

Reicks, G. W., Clay, D. E., Clay, S. A., Joshi, D. R., Moriles-Miller, J., Westhoff, S., ... & Bruggeman, S. A., 2021. Winter cereal rye cover crop decreased nitrous oxide emissions during early spring. Agron J. 113(5), 3900-3909. https://doi.org/10.1002/agj2.20658

Remus, R., Kaiser, M., Kleber, M., Augustin, J., Sommer, M., 2018. Demonstration of the rapid incorporation of carbon into protective, mineral-associated organic carbon fractions in an eroded soil from the CarboZALF experimental site. Plant Soil. 430(1), 329-348. https://doi.org/10.1007/s11104-018-3724-4

Rocci, K. S., Lavallee, J. M., Stewart, C. E., Cotrufo, M. F., 2021. Soil organic carbon response to global environmental change depends on its distribution between mineral-associated and particulate organic matter: A meta-analysis. Sci. Total Environ. 793, 148569. https://doi.org/10.1016/j.scitotenv.2021.148569

Ruis, S. J., Blanco-Canqui, H., Creech, C. F., Koehler-Cole, K., Elmore, R. W., Francis, C. A., 2019. Cover crop biomass production in temperate agroecozones. Agron J. 111(4), 1535-1551. https://doi.org/10.2134/agronj2018.08.0535

Ruis, S. J., Blanco-Canqui, H., Koehler-Cole, K., Jasa, P. J., Slater, G., Elmore, R. W., Ferguson, R. B., 2020. Winter cover crop root biomass yield in corn and soybean systems. Agrosystems, Geosciences & Environment, 3(1), e20101. https://doi.org/10.1002/agg2.2010

Samson, M. É., Chantigny, M. H., Vanasse, A., Menasseri-Aubry, S., Angers, D. A., 2020. Coarse mineral-associated organic matter is a pivotal fraction for SOM formation and is sensitive to the quality of organic inputs. Soil Biol. Biochem. 149, 107935. https://doi.org/10.1016/j.soilbio.2020.107935

Sanderman, J., Baldock, J.A., & Amundson, R., 2008. Dissolved organic carbon chemistry and dynamics in contrasting forest and grassland soils, Biogeochemistry, 89, 181–198. https://doi.org/10.1007/s10533-008-9211-x

Sastre, B., Marques, M.J., Garcia-Diaz, A., Bienes, R., 2018. Three years of management with cover crops protecting sloping olive groves soils, carbon, and water effects on gypsiferous soil. Catena 171, 115–124. https://doi.org/10.1016/j. catena.2018.07.003.

Schulte, R. P., O'Sullivan, L., Coyle, C., Farrelly, N., Gutzler, C., Lanigan, G., ... & Creamer, R. E., 2016. Exploring climate-smart land management for atlantic europe. Agric. Environ. Lett. 1(1), 160029. https://doi.org/10.2134/ael2016.07.0029

Sciarresi, C., Proctor, C., Haramoto, E. R., Lindsey, L. E., Carmona, G. I., Elmore, R., ... & Salmerón, M., 2020. Evaluating short-season soybean management adaptations for cover crop rotations with a crop simulation model. Field Crops Res. 250, 107734. https://doi.org/10.1016/j.fcr.2020.107734

Seifert, C. A., Azzari, G., Lobell, D. B., 2018. Satellite detection of cover crops and their effects on crop yield in the Midwestern United States. Environ. Res. Lett. 13(6), 064033

Six, J., Bossuyt, H., Degryze, S., Denef, K., 2004. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. Soil tillage res. 79(1), 7-31. https://doi.org/10.1016/j.still.2004.03.008

Skjemstad, J. O., Gillman, G. P., Massis, A., Spouncer, L. R., 2008. Measurement of Cation Exchange Capacity of Organic-Matter Fractions from Soils using a Modified Compulsive Exchange Method. Commun. Soil Sci. Plant Anal. 39(5-6), 926-937. https://doi.org/10.1080/00103620701881279

Smith, P., Adams, J., Beerling, D. J., Beringer, T., Calvin, K. V., Fuss, S., ... & Keesstra, S., 2019. Land-management options for greenhouse gas removal and their impacts on ecosystem services and the sustainable development goals. Annu. Rev. Environ. Resour. 44, 255-286. https://doi.org/10.1146/annurev-environ-101718-033129

Smith, R. E., 1999. Rapid measurement of soil sorptivity. Soil Sci. Soc. Am. J. 63(1), 55-57. https://doi.org/10.2136/sssaj1999.03615995006300010009x

Soil Survey Staff, 1999. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. 2nd edition. Natural Resources Conservation Service. U.S. Department of Agriculture Handbook 436.

Sokol, N. W., Bradford, M. A., 2019. Microbial formation of stable soil carbon is more efficient from belowground than aboveground input. Nat. Geosci. 12(1), 46-53. https://doi.org/10.1038/s41561-018-0258-6

Soong, J. L., Marañon-Jimenez, S., Cotrufo, M. F., Boeckx, P., Bodé, S., Guenet, B., ... & Janssens, I. A., 2018. Soil microbial CNP and respiration responses to organic matter and nutrient additions: Evidence from a tropical soil incubation. Soil Biol. Biochem. 122, 141-149. https://doi.org/10.1016/j.soilbio.2018.04.011

Souza, I. F., Almeida, L. F. J., Jesus, G. L., Kleber, M., Silva, I. R., 2017. The mechanisms of organic carbon protection and dynamics of C-saturation in Oxisols vary with particle-size distribution. Eur. J. Soil Sci. 68(5), 726-739. https://doi.org/10.1111/ ejss.12463

Spargo, J. T., Cavigelli, M. A., Mirsky, S. B., Maul, J. E., Meisinger, J. J., 2011. Mineralizable soil nitrogen and labile soil organic matter in diverse long-term cropping systems. Nutr. Cycling Agroecosyst. 90(2), 253-266. https://doi.org/10.1007/s10705-011-9426-4

Stringham, T. K., Krueger,W. C., Shaver, P. L., 2003. State and transition modeling: An ecological process approach. Rangeland Ecology & Management, 56.2, 106–113.

Tabatabai, M. A., 1994. Soil enzymes. Methods of soil analysis: Part 2 Microbiological and biochemical properties, 5, 775-833. https://doi.org/10.2136/sssabookser5.2.c37

Thomas, G. W., 1983. Exchangeable cations. In A. L. Page et al. (Eds.) Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties (pp.159-165). https://doi.org/10.2134/agronmonogr9.2.2ed.c9

Trumbore, S., 2009. Radiocarbon and soil carbon dynamics. Annu. Rev. Earth Planet. Sci. 37, 47-66. https://doi.org/10.1146/annurev.earth.36.031207.124300

Tubiello, F. N., Salvatore, M., Ferrara, A. F., House, J., Federici, S., Rossi, S., ... & Smith, P., 2015. The contribution of agriculture, forestry and other land use activities to global warming, 1990–2012. Glob Chang Biol. 21(7), 2655-2660. https://doi.org/10.1111/gcb.12865

USDA-NASS, 2019. 2017 Census of Agriculture, Summary and State Data. U.S. Department of Agriculture National Agricultural Statistics Service. https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf (accessed 28 January 2022).

USDA-NRCS, 2011. Cover crop planting specification guide *(NH-340)*. USDA-NRCS. https://www.nrcs.usda.gov/Internet/FSE_ DOCUMENTS/stelprdb1081555.pdf

Villarino, S. H., Pinto, P., Jackson, R. B., Piñeiro, G., 2021. Plant rhizodeposition: A key factor for soil organic matter formation in stable fractions. Sci. Adv. 7(16), eabd3176. https://www.science.org/doi/10.1126/sciadv.abd3176

von Lützow, M., Kögel-Knabner, I., Ekschmitt, K., Flessa, H., Guggenberger, G., Matzner, E., & Marschner, B., 2007. SOM fractionation methods: Relevance to functional pools and to stabilization mechanisms. Soil Biology & Biochemistry, 39, 2183–2207. https://doi.org/10.1016/j.soilbio.2007.03.007

Wagai, R., Mayer, L. M., Kitayama, K., 2009. Nature of the “occluded” low-density fraction in soil organic matter studies: a critical review. Soil Sci. Plant Nutr. 55(1), 13-25. https://doi.org/10.1111/j.1747-0765.2008.00356.x

Wallander, S., Smith, D., Bowman, M., & Claassen, R., 2021. Cover crop trends, programs, and practices in the United States. (EIB 222), USDA, Economic Research Service.

Wang, X. G., Lü, X. T., Zhang, H. Y., Dijkstra, F. A., Jiang, Y. G., Wang, X. B., ... & Han, X. G., 2020. Changes in soil C: N: P stoichiometry along an aridity gradient in drylands of northern China. Geoderma, 361, 114087. https://doi.org/10.1016/j.geoderma.2019.114087

Whalen, J. K., Bottomley, P. J., Myrold, D. D., 2000. Carbon and nitrogen mineralization from light-and heavy-fraction additions to soil. Soil Biol. Biochem. 32(10), 1345-1352. https://doi.org/10.1016/S0038-0717(00)00040-7

Willson, T. C., Paul, E. A., Harwood, R. R., 2001. Biologically active soil organic matter fractions in sustainable cropping systems. Appl. Soil Ecol. 16(1), 63-76. https://doi.org/10.1016/S0929-1393(00)00077-9

Wolf, S. A., Ghosh, R., 2020. A practice-centered analysis of environmental accounting standards: integrating agriculture into carbon governance. Land Use Policy, 96, 103552. https://doi.org/10.1016/j.landusepol.2018.08.003

Wooliver, R., & Jagadamma, S., 2023. Response of soil organic carbon fractions to cover cropping: A meta-analysis of agroecosystems. Agriculture, Ecosystems & Environment, 351, 108497. https://doi.org/10.1016/j.agee.2023.108497

Wright, C. K., Wimberly, M. C., 2013. Recent land use change in the Western Corn Belt threatens grasslands and wetlands. Proc. Natl. Acad. Sci. 110(10), 4134-4139. https://doi.org/10.1073/pnas.1215404110

Wu, G. L., Liu, Y., Tian, F. P., Shi, Z. H., 2017. Legumes functional group promotes soil organic carbon and nitrogen storage by increasing plant diversity. Land Degrad. Dev. 28(4), 1336-1344. https://doi.org/10.1002/ldr.2570

Yang, Y., Tilman, D., Furey, G., Lehman, C., 2019. Soil carbon sequestration accelerated by restoration of grassland biodiversity. Nat. Commun. 10(1), 1-7. https://doi.org/10.1038/s41467-019-08636-w

Yoder, R. E., 1936. A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses 1. Agron J. 28(5), 337-351. https://doi.org/10.2134/agronj1936.00021962002800050001x

Yu, W., Huang, W., Weintraub-Leff, S. R., Hall, S. J., 2022. Where and why do particulate organic matter (POM) and mineral-associated organic matter (MAOM) differ among diverse soils?. Soil Biol. Biochem. 172, 108756. https://doi.org/10.1016/j.soilbio.2022.108756

Zhang, X., Lark, T. J., Clark, C. M., Yuan, Y., & LeDuc, S. D. (2021). Grassland-to-cropland conversion increased soil, nutrient, and carbon losses in the US Midwest between 2008 and 2016. Environmental Research Letters, 16(5), 054018. 10.1088/1748-9326/abecbe

Zhou, Q., Guan, K., Wang, S., Jiang, C., Huang, Y., Peng, B., ... & Cai, Y., 2022. Recent rapid increase of cover crop adoption across the US Midwest detected by fusing multi-source satellite data. Geophys. Res. Lett. e2022GL100249. https://doi.org/10.1029/2022GL100249

CHAPTER 5 : EXPLORING THE INFLUENCE OF SOCIAL NETWORKS TO SUSTAIN SOIL HEALTH MANAGEMENT

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Abstract

On-farm research and federal conservation programs are tools for motivating behavior, in particular farmer's awareness of and initial use of soil health management practices. Adoption and continued use of practices through time, indicates long-term success of these programs, which is in part influenced by farmer's social networks. However, such programs rarely consider the social-ecological outcomes needed to understand farmer's network and social interactions, soil health-related beliefs, attitudes, and behavioral changes. Drawing on Diffusion of Innovation and Value-Belief-Norm theories, this case study explores the influence of social and informational networks on farmers' responses to sustained use of soil health practices. In-depth interviews, interactive activities, and project reports were conducted with participants of a partnership integrating soil health on-farm research and outreach in a Midwestern agroecosystem. We identified five drivers supporting farmer's social networks influences on sustained use of soil health practices. These were land tenure, perceived acceptance, family farming traditions, co-learning, and on-farm experimentation and adaptive management. We also identified other farmers on the community, family members, university extension, crop advisor/consultant, and conservationists within NRCS, who were perceived to have greater impact on farmer's decision-making than other stakeholder groups. Some of these influential groups ranked cover crops and no-tillage as practices having the largest impact on soil health and were more likely to recommend them to farmers. Finally, multiple soil and agronomic responses that indicated improvements in soil health were documented from the five-year on-farm experiments conducted through the partnership program. We linked learnings from the implementation of soil health

practices and factors related to farmers’ beliefs and informational networks. These findings identified important lessons for efforts prioritizing conservation approaches on farmlands that meet both agricultural sustainability and grain crop production goals.

Introduction

Soil health has been presented in recent years as an approach to farm management that can address many concurrent agricultural challenges, with substantial momentum for directing agricultural research and policy agenda (Basche et al., 2020; Wander et al., 2019). The elevated discourses on the future of agriculture and transformations of food systems have led many legislative efforts across the US to explore approaches to support soil health research and education on farmlands (Soil for climate, 2019). Recently, government and private-led initiatives have encouraged soil carbon sequestration through financial incentives and farming programs (Wolf & Ghosh, 2020), which spurred further adoption of soil health-promoting practices on farms and revitalized the conversation around the climate impacts to agroecosystems (Buck & Palumbo-Compton, 2022). These efforts demonstrate the growing interest in innovative policies and initiatives to develop a network of synergistic partnerships to enhance research and adoption of soil technologies in agriculture, with emphasis on soil health approaches that help meet both agricultural sustainability and production goals.

The US Department of Agriculture (USDA) is the government agency incentivizing the adoption of soil health practices on farmlands (Czap et al., 2019). The Conservation Reserve Program (CRP), Environmental Quality Incentives Program (EQIP), and Conservation Stewardship Program (CSP) are three examples of programs administered by the USDA-Natural Resources Conservation Service (NRCS), which represents a $6.7 billion dollar budget allocated for conservation programs (CSR, 2018, 2019; U.S. Congress, 2019). Most of these programs are designed to provide financial incentives (e.g., monetary, nonmonetary, or cost share agreements) to encourage voluntary behavior change by offsetting costs and risks associated with initial adoption of a practice. Another way to promote adoption of soil technologies, particularly awareness of the need and initial use of soil health management practices, is through extension and on-farm research programs led by land-grant universities (Thompson et al., 2019). Extension-developed on-farm research offers the opportunity to position farmers as local and personal stakeholders in the development of knowledge on soil health. Including farmers as active participants in the development of knowledge is seen as an effective method of technology and innovation transfer (Wood et al., 2014). Further, the use of farmer-initiative on-farm research ensures that researchers are focusing on the relevant topic of soil health and that farmers are benefiting from the knowledge exchanged during the research process (Thompson et al., 2019). These available programs, either led by federal agencies or land-grant universities, tend to be justified based upon soil conservation status and typically evaluated based on biophysical outcomes (e.g., acres treated, dollars invested, knowledge gained) (Dayer et al., 2017). However, time and resources have been allocated yearly to these farmer-organization partnerships, yet deterioration of fundamental soil properties continues (Evans et al., 2020).

Soil health incentive programs need new frameworks to holistically understand and conceptualize factors that influence farmer’s decision-making, which are in part influenced by their social networks and sources of information. With the largely untapped potential of federal incentive programs to confer greater impacts on soil health (Basche et al., 2020) and the social mechanisms and human dimensions underlying farmers’ social networks and information processing on soil health remaining often overlooked, a qualitative examination is needed for shaping more effective approaches to overall land management and health (Dayer et al., 2018). Further, including social science research within soil health initiatives can help in successfully designing conservation program strategies, selecting producer’s behavioral targets, and evaluating results by measuring conservation behavior (Akerlof & Kennedy, 2013). Because of the complexity of agricultural systems and management choices affecting soil health, this research extends beyond laboratory and field settings to explore a unique collaborative soil health initiative involving farmers, conservationists within NRCS, and extension on-farm research network in Nebraska. The goal of the study was to examine how farmer networks and social interactions exert influence on sustaining use of soil health practices.

Theoretical Framework

Agricultural conservation programs can be effectively designed and implemented through the lens of social science theories that promote agricultural innovations. Scholars have advocated for theoretically grounded research exploring the human dimensions of agricultural conservation practices (Floress et al., 2018; Prokopy et al., 2019). Multiple theoretical perspectives can be applied when discussing the adoption, sustained use, and communication of soil health practices. This current research draws upon ideas from social science theories for environmental sustainability (Stern, 2018), particularly Diffusion of Innovation and Value-Belief-Norm theories, to holistically understand farmer's affiliative networks and its influence on their beliefs about and responses to sustaining soil health management. In this study, we define affiliative networks as groups of individuals or entities that might directly or indirectly influence farmers' decision-making in regards to their farming enterprise.

Diffusion of Innovation Theory

Diffusion of Innovation Theory covers a wide expanse of topics related to the diffusion and adoption of new ideas and technologies. In this study, the theory is applied primarily to understand the social networks in which soil health-related ideas or management practices are sustained through time (i.e., initial and continued use of the innovation). Aspects of the Diffusion of Innovation Theory are important when considering the diffusion and adoption of soil conservation behaviors (Rogers, 2003). The social system can be described in terms of nodes (e.g., individuals or groups) and ties (e.g., relationships between individuals or groups). Network structures vary tremendously, but its mapping can help to identify effective ways to diffuse soil health-promoting practices. For example, early adopters of soil health practices can serve as opinion leaders, influencing others' evaluation of new ideas, and accelerating the diffusion process (Valente & Davis, 1999). Further, farmers enrolled in conservation programs can influence other farmers in the community. Thus, strategies such as workgroups or peer-learning groups that support leadership opportunities among producers enrolled in agricultural conservation programs can help mobilize low conservation level producers (Czap et al., 2018).

Information on farmers’ affiliative networks in discussions about soil health practices is important to understand who can deliver information to farmers and help to develop a network of agricultural conservation professionals (Prokopy et al., 2019). Eanes et al. (2019), studying the perception of crop advisors as credible sources of information on soil health, found that crop advisors positively perceived their role in delivering information on soil health practices. The study also highlighted the challenges of crop advisors, as conservation intermediaries, in collaborating with private and governmental sectors. Wood et al. (2014) studied a pastoral farming collaborative experiment undertaken by a group of producers and scientists in New Zealand. A mixed-method approach was applied to explore the knowledge exchange network and the knowledge perspectives that drive farmers networking. Results revealed that farmers shared information about their demonstration field with over 190 people, comprised primarily of other fellow farmers. The study also revealed that social networks densely tied and comprised of homogeneous people usually grow more compared to loosely tied and diverse network groups.

Recognizing the importance of producer’s affiliative network, the North Dakota State University (NDSU) Soil Health Program relied on a network-based approach to successfully encourage conversation and adoption of soil health practices. Wick et al. (2019) analyzed this knowledge network using data obtained from 32 discussion groups, totaling 156 individuals, over two years of the program. The social network analysis helped to identify the most influential scientists, farmers, crop consultants, and extension specialists of the group. Results revealed that over 25% of the farmers adopted soil-health practices because of being part of the network.

Value-Belief-Norm Theory

Even though farmers are constantly interacting with other agricultural stakeholders (e.g., farmers, certified professionals, suppliers) both individually and collectively, their pro-environmental attitudes and behaviors are affected by values, beliefs, and norms. The Value-Belief-Norm theory was first introduced by Stern et al. (1999) to explain the drivers of pro-environmental behaviors. Values, beliefs, and norms are the three main components part of the theoretical framework. According to the theory, individuals' values affect their general beliefs about an issue, in this case, soil degradation. Individuals' environmental beliefs influence the extent to which a person recognizes a problem, becomes aware of its consequences, and recognizes its role to mitigate or solve the issue. Problem awareness is generally promoted by collective values, known as individuals' stable beliefs, used to evaluate attitudes and behaviors. Biospheric, altruistic, and egoistic are the three personal value orientation incorporated into the theory.

A recent meta-analysis evaluating the adoption of agricultural conservation practices among 279 qualitative studies across the US showed that attitudes toward an agricultural conservation program or practices as well as farmer identity were the strongest predictors of adoption (Prokopy et al., 2019). In the study, farmers who self-identified as not being primarily motivated by financial aspects had positive attitudes toward soil health practices or programs (Prokopy et al., 2019). There was also evidence that farmers whose identity fits into risk-tolerant were more willing to adopt soil health management practices (Belknap & Saupe 1988; Kim et al., 2005). Further, a growing body of research suggested that farmers with positive attitudes related to stewardship and "other interests" were more likely to adopt soil health practices than those with high levels of self-interest (Floress et al. 2019; Reimer & Prokopy 2012; Thompson et al., 2015). Finally, in terms of environmental awareness, research on soil and water conservation practices adoption has shown a positive relationship between farmer's environmental awareness and the likelihood of practice adoption (Baumgart-Getz et al., 2012; Knowler & Bradshaw 2007; Prokopy et al., 2008).

Farmer decisions regarding enrollment in on-fam research and/or incentive programs and sustained use of soil health practices are shaped by the social system in which an idea or practice is diffused. By applying the concepts of Diffusion of Innovation theory, we can better understand how farmers network their soil conservation program experience and management decisions with a larger field of contacts. Further, we can understand the social interactions that exert both a positive and negative influence on farmer decision-making regarding program engagement and soil health practice adoption. Even though agricultural conservation initiatives across the US have historically aimed for the development of stewardship ethics and pro-environmental values, not all farmers are willing to or already adopting soil health practices identify themselves primarily as land stewards (Dayer et al., 2018; Prokopy et al., 2019). Incorporating the Value-Belief-Norm theory in our study can aid in identifying farmers' identity measures (e.g., altruistic, steward, innovative, leaders, self-interest) associated with soil health practice adoption. Asking farmers to think about their feelings associated with the adoption/or no adoption of soil health management such as reduced tillage, cover crop, crop-livestock integration, and diversified crop rotation can show relationships to farmer's behavioral intention.

Purpose and Objectives

The purpose of this research was to explore how social and informational network influence farmers sustaining use of soil health practices. Building on the literature reviewed above, we adapt concepts from the Diffusion of Innovation and Value-Belief-Norm Theory to address the following objectives:

1) Describe factors that support or hinder farmer's network and social interactions influences on sustained use of soil health practices.
2) Describe social network impacts on farmers both, overall and soil health-related farming decisions, and their priority ranking of candidate management practice to improve soil health.
3) Describe learnings from soil health and yield impacts documented as part of a five-year on-farm experimentation project.

Methods

This study was part of a larger on-farm research investigation (Krupek et al., 2022a, 2022b) to understand the biological and ecological processes that govern soil health-related management practices in the context of a statewide on-farm research initiative. Given that this collaborative project in 2017–2022 was a catalyst for successful and ongoing partnerships that continue to evolve, a close examination of these early efforts provides lessons for future initiatives and program efforts focused on soil conservation in agricultural landscapes. Thus, an exploratory investigation with a case study approach was used to accomplish the purpose of this study. Case study research seeks to comprehensively describe the interactions of a bounded unit in relation to a phenomenon (Merriam & Tisdell, 2016) by collecting multiple data sources (Burkholder, 2019). We analyzed in-depth interviews, interactive activities, and impact reports to explore specific factors and relationships - often overlooked in social-ecological research - that compose the process of soil health management behavioral evolution (i.e., adoption and continued/sustained use), which makes qualitative research and case study an appropriate design for this research. In addition, the use of semi-structured in-depth interviews gave farmers the flexibility to discuss their thoughts and feelings around the questions and for the interviewer to adapt and ask probing questions as needed.

Case study context

The Nebraska Soil Health Initiative (SHI) provides a unique case of public research and outreach investment to identify, implement, and evaluate field management practices that enhance soil health on agricultural lands. The initiative is a cross-sector collaboration between the University of Nebraska (UNL) On-Farm Research Network - the Nebraska Extension state-wide efforts with on-farm research (Thompson et al., 2019), the USDA's Natural Resources Conservation Service (NRCS), and Nebraska farmers. The initiative began in 2016 when NRCS conservationists and Nebraska Extension Educators and Specialists met to discuss ways to bring farmer-initiated on-farm research (Thompson et al., 2019) to federal conservation programs such as the NRCS Environmental Quality Incentive Program (EQIP), providing education on and promoting adoption of soil health practices. Those initial conservations led to 17 farmers, representing a total of 1793 acres of farmland, agreeing to participate in a 5-year demonstration project with randomized, replicated side-by-side comparisons of a new management strategy that meet several soil health goals (e.g., planting cover crops, diversifying the crop rotation, integrating livestock) versus their traditional cropland management strategy during the 2017-2022 growing seasons (Figure 5.1).

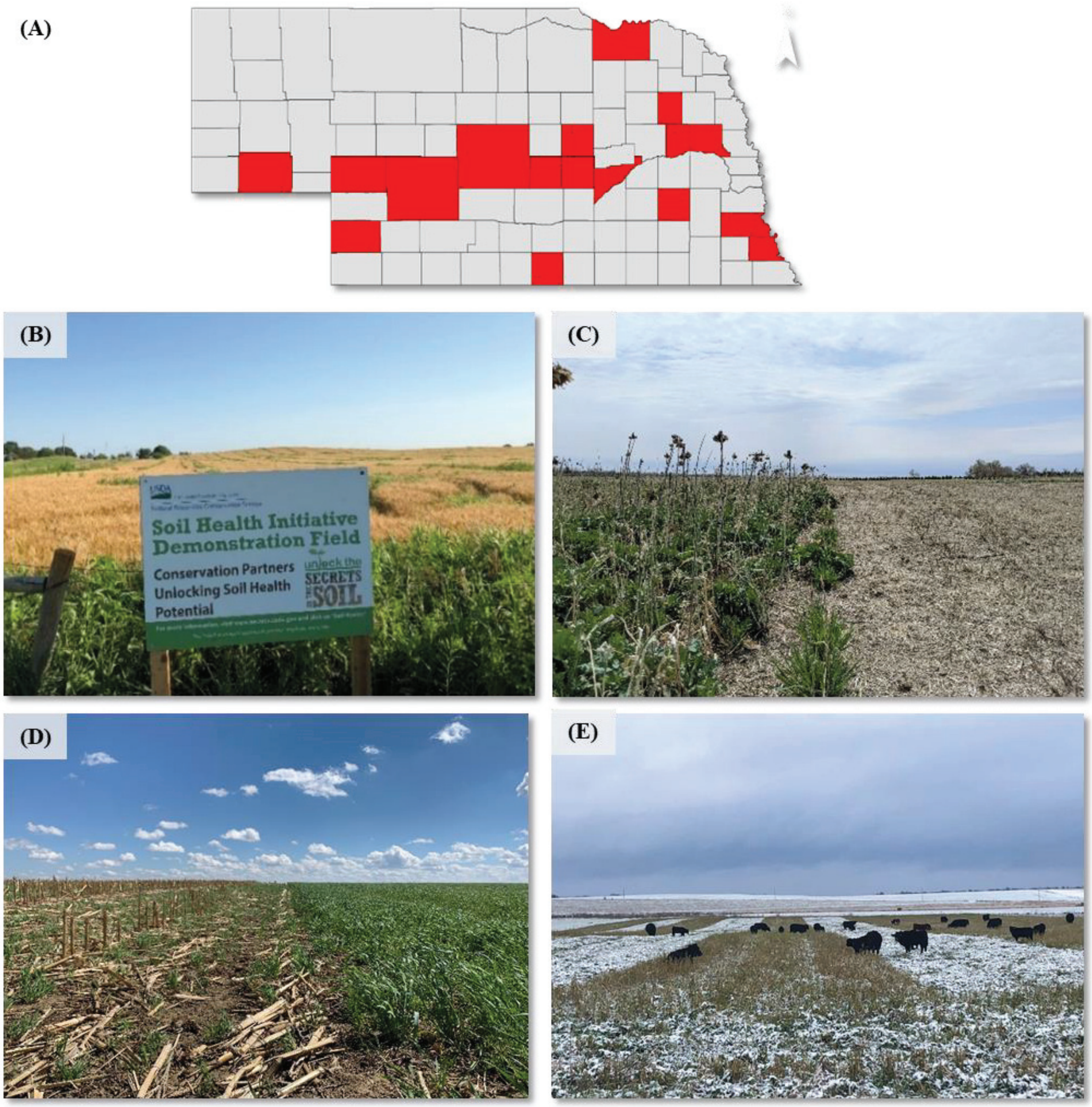

Figure 5.1. (A) Map of on-farm experiments part of the Soil Health Initiative. Farm county locations are indicated by red color. Soil management comparisons on farms (B) multi-species cover crop vs no cover crop (Howard County), (C) interseeded vs drilled cover crop (Merrick county), (D) corn/soybean vs corn/soybean/small grain rotation with multi-species cover crop (Dodge County), (E) winter hardy vs winter terminated cover crop with grazing component (Nemaha County).

Many partners, including Extension Educators and Specialists, scientists, and graduate students from the University of Nebraska-Lincoln, staff members from USDA-NRCS, and local farmers, were involved, to some extent, on different facets of this project, each bringing their own strengths to the endeavor. Due to the project participation (e.g., agency and citizen) and because collaborator farmers with cost-share funding work within the regulatory framework of Farm Bill programs, the project can be classified as a mixed partnership (Moore & Koontz, 2003) or largely community-driven agency or citizen partnership (Church & Prokopy, 2017). Sustained management, which we refer to farmer's continued learning and experimentation with soil health practices beyond the spatial and temporal scope of the initiative, was key to the success of this state-wide soil health program. While several learning opportunities can be drawn from other state-wide soil health programs (Kladivko et al., 2019), the long-term success of these programs to initiate and maintain soil health practices in privately managed lands requires understanding of the social mechanisms and human dimensions underlying farmers' communication networks and information processing on soil health.

Data collection and analysis

This paper includes data analysis from a unique multi-stakeholder initiative involving farmers, extension, and conservation professionals in Nebraska. Through analysis of meeting observations, project documents, and in-depth interviews with Nebraska farmers involved with the USDA-NRCS Soil Health Initiative and UNL On-Farm Research Network that were collected/completed between 2017 and 2022, we examined how farmers' network and social interactions exert influence on sustaining use of soil health practices. Ultimately, results from these analyses are intended to improve learning and network opportunities among growers, collaborators, and practitioners involved in on-farm collaborative research and incentive programs; known to be key for successful learning and continued experimentation to address the dynamism, complexity, and non-linearity of social-ecological systems (Pahl-Wostl & Hare 2004; Folke et al. 2005; Armitage et al. 2010).

Interviews

Researcher received approval from the University of Nebraska-Lincoln Institutional Review Board to conduct the study (IRB 20220221745EX, Supplementary Material). To address the first objective of this study, we interviewed 8 out of the 10 farmers participating actively in the SHI on-farm field research in 2017–2022 (Krupek et al., 2022a). This group was selected to gather information-rich cases of Nebraskan farmers currently participating on this multi-stakeholder initiative. Each interview lasted between 1.5 and 2 hours and was audio and video recorded for transcription purposes. All participants provided their consent to and were compensated for their time participating in the study; numbers are used when referring to the names of specific individuals. Semi-structured in-depth interviews with open-ended questions were administered by the principal researcher and conducted remotely through video calls. The semi-structured interviews asked between 26 and 29 questions to investigate farmer's contacts and sources of soil health knowledge, farmer's information transmission about soil health practices, and farmer's perspectives about knowledge exchange. Additional questions asked about the farmer's experience with the SHI program and the management practices tested on their farm (Supplementary Material). Interviews were conducted until no new themes emerged in the data; a process termed theoretical saturation (Birks & Mills, 2015).

Computer software NVivo was used to qualitatively code the in-depth interview transcripts, helping the research team with coding organization, audit trail, and code analyzes. Common themes were identified using a constant comparative method of analysis (Birks & Mills, 2015; Creswell, 2013). Theoretical categories were used to integrate aspects of the Value-Belief-Norm and Diffusion of Innovation theories. We identified several key themes used to thematically code the interview transcripts (Table 5.2).

In this study we used peer debriefing, clarifying researcher bias, member checking, and audit trails to ensure qualitative validity and reliability (Creswell, 2013). Peer debriefing for this study was an assistant professor in the Agricultural, Leadership, Education, and Communication Department at the University of Nebraska-Lincoln. The peer reviewer works with Agricultural and Environmental Sciences Communications and has collaborated with Extension faculty across Nebraska. Members of the research team have past experiences, opinions, and knowledge that affect qualitative data analyses. An author's subjectivity statement is included to clarify researcher bias and should be considered when drawing conclusions and interpreting findings from this study (Supplementary Material). The summary of data analysis and a transcript of the interview was emailed to each participant farmer for their review and feedback. This was the tool used to access member checking (Stake, 1995). Finally, a detailed description of the coding process, along with the decisions made and the tracked themes, was kept in NVivo for audit trails.

Research Update Annual Meeting

In addition to the in-depth interviews, we also collected data from two interactive mapping activities to fulfill the second objective of this study. Decision-making and conservation practice exercises were performed with farmers and stakeholder groups, respectively (Supplementary Material). Both activities were conducted at the 2020 On-Farm Research Network Annual Meeting, year when most of the SHI demonstration fields were reaching halfway in their five-year project (Table 5.1). The meeting which had a special soil health and cover crop update focus and were presented by the OFRN and NRCS, was attended by 101 attendees. Activities were voluntarily performed by a total of 30 farmers and 19 extension personnel, conservationists and crop advisors, and was facilitated by the principal researcher. Thus, activities were applied to a broader range of participants, which included but were not limited those pertaining to the SHI - farmers, conservationists, extension personnel and agribusiness involved on or interested in learning from the Soil Health Initiative University of Nebraska On-Farm Research Network.

Briefly, the decision-making interactive mapping activity provided farmers with several sheets of paper indicating different groups of people (e.g., natural resource district, commodity groups, family member or farm partner, commodity groups) along with circular grid paper consisting of concentric circles labelled with a scale from 1 to 5 moving outwards and with ‘My decisions about my operation’ at the center. Farmers were asked a two-part task, to score how large of an impact the groups of people have first, on their overall decision-making and, second, on their decision-making related to soil health management by placing higher-impact groups closer to the center of the circular grid. Similarly, as part of the conservation practice activity, extension personnel, conservationists and crop advisors were asked to first evaluate their perception on the impact of management practices (e.g., reduced-till, cover crop, mulching, alternate crop rotation, compost) on improving soil health and second, their willingness to recommend those practices to a farmer. Practices placed closer to the center of the grid were assigned a low score in the 1 to 5-point scale and viewed as having a larger impact on soil health or more likely to be recommended. Descriptive statistics, namely mean values, were used to rank groups of people impact on farming decisions and management practice impact on soil health. Mean values were calculated using Microsoft Excel and displayed in radar plots (Figures 5.2 and 5.3) to aid in interpretation of results.

OFRN Extension on-farm and impact reports

To fulfill the third objective of this study, we performed content analysis - primarily information on crop yield and soil property responses to on-farm management comparisons - of 32 SHI summary reports that were compiled yearly from 2018 to 2021. Briefly, the SHI on-farm research experiments rationale, objectives, results, and observations were compiled yearly into annual research reports, namely On-Farm Research Results Book, along with all other on-farm studies within the University of Nebraska-Lincoln Extension (Nebraska Extension On-Farm

Research, 2021). Data collection and analysis presented in each 2-5 page on-farm report (i.e., primarily crop yield and soil property responses to on-farm management comparisons) were a collaborative endeavor among students, faculty, staff, and extension educators from the UNL system that underwent internal data review process before being shared at the university's online repository (Soil Health Initiative On-Farm Research Reports).

In addition to summary of data presented in the 32 SHI on-farm reports, we also examined impact reports data from the 2020 and 2021 On-Farm Research Network Annual Meetings. Briefly, data from the SHI reports covering the fourth and fifth year of implementation, monitoring and evaluation of soil health management practices on farms (Table 5.1) were presented and discussed as part of the 2020 and 2021 On-Farm Research Network Annual Meetings. These are series of science-oriented events hosted by the On-Farm Research Network (OFRN) at several locations across the state to share on-farm research findings (Thompson et al., 2019). These gatherings bring together a broader audience of farmers, university, and agricultural stakeholders (e.g., agronomists, industry, government employees) than those specifically involved in the SHI and provide farmers with the opportunity to present their on-farm research projects as speakers, followed by table discussions among attendees. Post-meeting evaluation survey instrument was distributed to event attendees (N = 101 and 300 for the 2020 and 2021 meetings, respectively), and the survey included several types of questions from yes/no, rating, to open-ended questions to gauge meeting attendee's demographics and general program evaluation and feedback. For this study, we focused on summarizing post-meeting survey questions related to cover crops and soil health, which are the possible SHI contributions to attendees' knowledge exchange from these annual meetings. A total of 47 and 62 attendees completed the survey in the 2020 and 2021 meetings, respectively.

Table 5.1. Soil Health Initiative (SHI) formally and informally organized encounters (main audience present).

Formally organized encounters	Informally organized encounters
Winter 2019 UNL on-farm research (OFR) Results Update Meeting*	Phone calls, text messages, emails before monitoring site visits (NRCS personnel, UNL Faculty/Students/ Extension personnel)
Winter 2020 UNL OFR Results Update Meeting*	Conversations during monitoring site visits (NRCS personnel, UNL Faculty/Students/ Extension personnel)
Winter 2021 UNL OFR Results Update Virtual Meeting*	
Regular Occurring Virtual Meetings (NRCS Soil Health Specialist and UNL Faculty/Students/Extension personnel)	
On-Farm Research Data Review on Cover Crop Studies (UNL Faculty, Students, Extension personnel)	
Soil Health Demonstration Farm Field Days*	

*variety of attendees: farmers, agribusiness (crop consultants, seed dealers, etc.), government employees, and university faculty and students.

Results and Discussion

Table 5.2. Factors supporting farmer’s social and informational networks influences on sustained use of soil health practices.

Key themes for data analysis	Definition	Evidence
Land tenure and rent	Interactions between land owner and land tenant at the interface of distinct motivations and beliefs related to soil health	Farmers have faced challenges in weighing financial and stewardship motivations with respect to landowner relationships when deciding to adopt soil health practices in the long term
Perceived acceptance/cost of perception	Farmers normative beliefs – what they think others would think of them, the perception of acceptance within specific relationships	Farmers can be interpreted by others as “weird or outliers” when adopting soil health practices
Family farming tradition	Style of farming and food production carried by farmer’s previous generations	Farmers expressed interests in either carrying on family member’s farming traditions or discontinuing them, depending on the practice known effects on soil health
Co-learning	Educational approaches involving shared soil health knowledge and experiences among farmers and/or agricultural stakeholders	Farmers openness to share with others experiences with soil health practices also openness to listen to both sides (i.e., learning from contrasting ideas related to soil health)
On-farm experimentation	Farmer’s involvement in hands-on learning experiences in their farming operation through extension on-farm research and conservation incentive programs	Farmer’s perceived benefits that involvement with on-farm education bring for sustained use of soil health practices

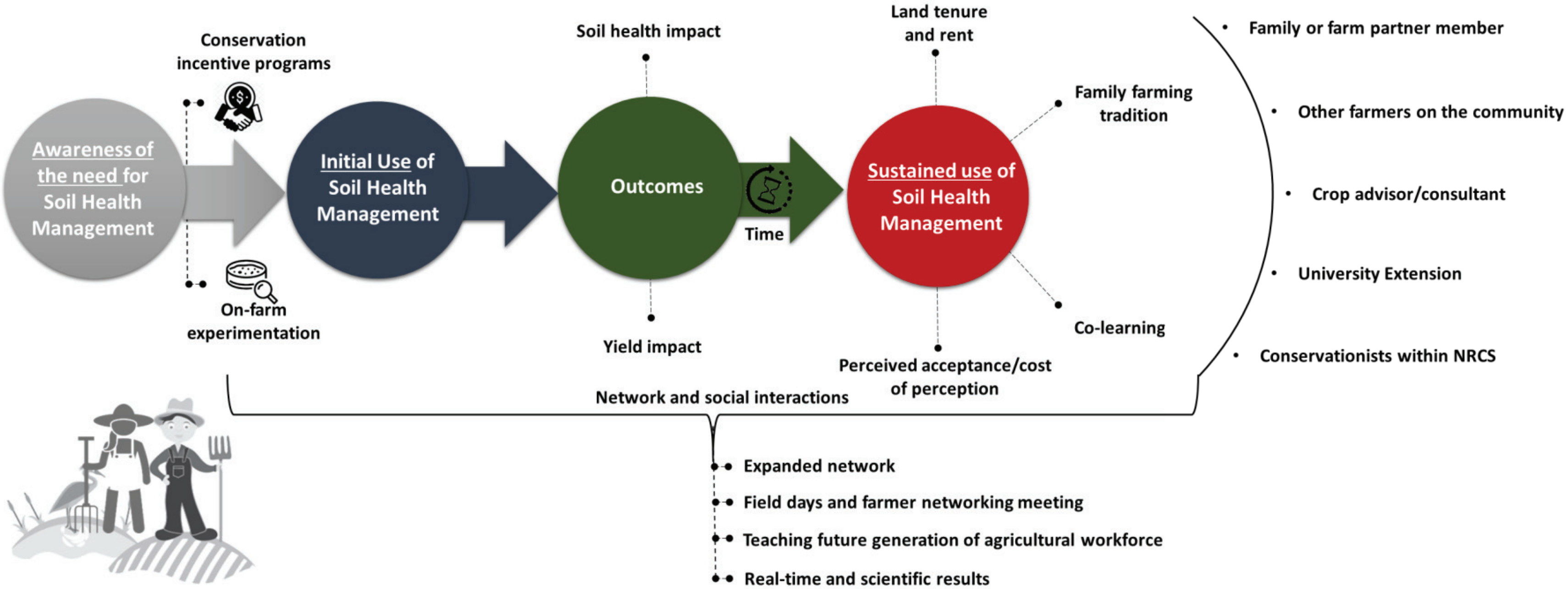

Figure 5.2. Conceptual framework of key factors and stakeholder groups supporting farmer's social and informational networks influences on sustained use of soil health practices.

Objective 1

Describe Factors That Support Farmer's Social and Informational Networks Influences on Sustained Use of Soil Health Practices

Land tenure and rent

Participant farmers identified land tenure - the relationship, whether legally or customarily defined, among people, as individuals or groups, with respect to land - a key factor on their social and informational networks influences on sustained use of soil health practices (Table 5.2, Figure 5.2). Often overlooked in agricultural research (Barnett et al., 2020), landowner-tenant relationships found in our study might seem to hinder long-term investments in soil health. The ultimate goal of both groups might be somewhat different – most interviewees demonstrated interest in protecting the land and natural resources, whereas counterpart farmers wanted to find a way to meet short-term production goals over long-term environmental sustainability. Several participants described landowner-tenant relationships as "antagonists" during interviews: "Some of [land managers] looking negatively at cover crops. They look more at soil as a chemical structure and not biological. You just can't get implementation of soil health practices when you look at land that way" (Farmer #6). A farmer also described the challenges with custom farming, an alternative to leasing farmland, particularly in investments in conservation practices that accumulate benefits relatively slowly over time (Chapman et al., 2022). For example, adding pollinator strips (e.g., flowering plants) on eroded areas of the farm, instead of the crop that the farmer normally sells - primarily corn and soybeans - is not considered a one-year payoff investment and therefore a practice that often conflicts with farm's income and production goals in the short term. As one participant explained:

> "On ground we own, on most of it, I've planted 45 to 60 feet of pollinator strips with broom or bluestem or something as grass. Those are surround most of the

> fields that we own that are on slopes. On ground that I custom, I'm not allowed to do that because they want all the acres planted" (Farmer #6).

Understanding land ownership and tenure in soil health management decision-making is imperative, given the high proportion – approximately 39% – of agricultural land in the US involving farmer–operator agreements (USDA-NASS, 2014). Consistent with prior research (Carlisle et al., 2022), structural factors such as the predominance of short-term lease agreements might restrict the adoption of soil health practices in the long run. As a farmer described it "each year is the most important thing, rather than looking far into the future. Maybe they'll start giving multiple year contracts more" (Farmer #6). Participant farmers who owned some of their land also expressed interest in including adoption of soil health promoting practices such as cover crops (e.g., plants grown to cover the soil after the main crop is harvested) as part of their rental agreement: "We said that whoever runs our ground has to do cover crops. That's what was going to be part of our lease agreement. We look for the person that will honor that rental agreement" (Farmer #2).

Establishing mutually beneficial goals is an important process that facilitates learning and collaboration across community boundaries (Hardie Hale et al., 2022). Even though farmers in our study have faced challenges in weighing short-term financial and long-term stewardship motivations when describing their landowner-tenant relationships, according to participant #7 there have been recently more opportunities to discuss soil health practices with landowners:

> "But there has been more opportunities lately with landowners that we currently rent land from to discuss. Sometimes because the neighbors told us that our fields were in really bad shape. So we had to explain, and there was a good opportunity to communicate. Actually, it's a lot better things going on out here than what you realize" (Farmer #7).

The opportunity to communicate with landowners ways that farmers are able to recoup their investments in soil health practices, particularly in degraded or marginal (i.e., "bad shape") lands can lead to more win-win scenarios and mutually beneficial lease agreements. These comments also reflect participants understanding that landowner-tenant relationships are critical, particularly for advancing implementation of conservation plans that meet several soil health goals in the long-term (Basche & Carter, 2021).

Perceived acceptance or cost of perception

Farmers' normative beliefs – what they think others would think of them – and the perception of acceptance within specific relationships was a theme that emerged during the interviews as key factor affecting farmers long-term adoption of soil health practices (Table 5.2, Figure 5.2). As farmer #2 explained:

> "Perceived acceptance. It's kind of a false thing. It's all about farming more ground faster, being the first one in the field, and the first one out of the field in the fall. It's kind of sad because some of the young kids starting out to farm are thinking that's what farming is all about. It's hard to change their mindset." (Farmer #2)

Some, like participant #7, described the process of perceived acceptance as "cost of perception":

> "The negative influence generally comes from other farmers. I call it a 'cost of perception'. So it's perceived as different, and weird, and bad. There's a perception, and it has a cost to me. There's farmers on all levels. There's some that are really into it [soil health], some that it's just kind of indifferent, and there's some that just "it doesn't make sense" (Farmer #7).

These comments reflect participants understanding that in many cases adopting practices for improving soil health might fall outside of what is perceived as "normal" within the farming community. This is in part due to the practical challenges in utilizing and managing cover crops, diversified crop rotations, and integrated crop-livestock practices within the timeframe available to the dominant maize-soybean systems in the Midwest (SARE-CTIC, 2020). For example, the short maize-soybean winter window to grow cover crops was expressed by farmer #5 who was able to drill cover crop seeds only in December, when heat units that drive plant growth is very low in the region. The practice of seeding cover crops was not well perceived by neighboring farmers. “One of the neighbors asked ‘what the heck I was doing out in the field with the drill in December?’. So when you do things out of the ordinary, you make the neighbors talk” (Farmer #5).

Other participants mentioned a certain sense of peer pressure from neighbors and other farmers in the community, particularly to anticipate planting and harvest operations of their corn and soybeans crop when the field conditions were not ideal (using heavy load machinery in wet fields and causing soil compaction). However, this sense of peer pressure was less evident among farmers with more integrative enterprises such as those with crop-livestock operations. According to Farmer #6,

> “One of my farmer friends that I talked to pretty often, he has hogs and sheep and I have cattle. We have other work to do, that's making us money by taking better care of our livestock. So we don't feel that pressure to go out and get a field as too many by having livestock” (Farmer #6).

Untimely this perceived acceptance or cost of perception affect not only farmers’ interaction with their neighbors and other farmers in the community, but also influence decision-making around specific soil health promoting practices. For example, management practices such as the use of no or reduced tillage, where farmers avoid plowing soils, is known to improve indicators of soil health such as soil aggregate stability, infiltration rates, and microbial indicators (Steward et al., 2018). However, adoption of no or reduced tillage also affects crop early growth and establishment that might not be perceived well by other farmers. Participant #7 had a typical response to the question on the perceived benefits and drawbacks of soil health promoting practices, particularly reduced tillage: “Not doing tillage sometimes doesn't look as good in the spring. So people who do tillage will typically have crops that look better early. That's back to that perception thing” (Farmer #7).

Increasing acreage of soil health practices such as cover crops, no-tillage, diversified crop rotation, and integrated crop-livestock systems is a current funding focus of research and outreach efforts from government, non-profit and private sector entities (Wander et al., 2019). More specifically, research related to the management of specific soil health practices has the potential to scale up adoption, advance equipment technology, and ultimately reduce the perceived acceptance or cost of perception hindering farmers’ long-term adoption of these practices.

Family farming tradition

Family farming tradition – the style of farming and food production carried by farmer’s previous generations – was another important factor supporting farmer’s social and informational networks influences on sustained use of soil health practices (Table 5.2, Figure 5.2). When we asked farmers for examples of specific soil health promoting practices they have tried or would like to try in their farm operation, a typical response was to connect their current decision-making with previous generation of farming traditions. As one farmer told us:

> “My dad actually back in the 50s used rye and we didn't have really herbicides much, but he plowed under and call a green manure. So he, at that time, had a lot of cattle, hogs and sheep, so he could cover a lot of acres with manure. What he didn't cover with manure he would have sown rye, and then work it into the soil in the spring. One thing he never got away from was using legumes and a crop rotation to fix nitrogen” (Farmer #6).

Farmers also expressed a nostalgia for pre-1950s farming systems as one farmer told us:

> "On my mother's side, they emigrated from Germany in the 1860s. They brought the practices from Germany. They were big on sweet clover and planting oats and rotating. Then and I find myself going back to what they were doing. It's going to be close to 200 years ago. We're reinventing the wheel that was used I know 200 years ago. That's what they did in Germany" (Farmer #3).

These comments reflect the role that family members exert on farm decision-making either the legacy of carrying on family farming practices, primarily diversified and integrated crop-livestock systems, or discontinuing them, more specifically tillage operations. As one farmer put it,

> "I started no-till back in the 90s and saw what I felt were great results. When I was young, my father was a plow and disk three times and hero till. There wasn't any dirt left basically, it was just powder. I didn't like what I saw with that and maybe was just wanting to change what my father did" (Farmer #3).

The interviewees' description above also demonstrated the changes in agricultural systems in our study region following the Green Revolution of the mid-20th century. Landscape complexity shifted from high diversity in the 1950 s and 1960 s, with corn (*Zea mays* L.), sorghum (*Sorghum bicolor* [L.] Moench), alfalfa (*Medicago sativa* L.), wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.), and soybean (*Glycine* max [L.] Merr.) integrated with livestock, to maize-dominated systems that comprise the current landscape (Hiller et al., 2009). The wide adoption of glyphosate-resistant crops also contributed to the increase in no-till or reduced-till systems in Midwestern US (Givens et al., 2009). Farmers in the study region have shown increased interest and adoption of soil health management practices such the addition of cool-season cash crops, no-till, and cover crops in the last decades according to the literature (Knowler & Bradshaw, 2007; Baumgart-Getz et al., 2012) and as demonstrated by interviewee's descriptions above. This growing focus on soil health also demonstrate the interest in addressing generations of industrialized agricultural systems focused on external inputs as described by participant #3:

> "Working with the biology and the soil, trying to get nitrogen out of the air and being able to cut 40 pounds of nitrogen on your fertilization program which I think this is awesome. It's expensive right now. You just keep whittling away at your nitrogen needs. Hopefully it gets you more competitive at the end" (Farmer #3).

Co-learning

According to interviewees, educational approaches involving shared soil health knowledge and experiences among farmers and agricultural stakeholders was another important aspect of farmer's social and informational networks that influenced their sustained soil health management decisions (Table 5.2, Figure 5.2). As one farmer said,

> "A lot of it [soil health learning] was through conferences and things like that. Ultimately, you're getting, most of the time, other farmers just showing what they had done, and learning that way. Not until the last 4 or 5 years I have had like a peer here in the area, that we could bounce ideas back and forth on top of each other. That's actually helped a lot to find somebody that's like minded, so then we can do our own experiments on the farm and learn from each other" (Farmer #7).

Farmers are largely interacting and learning with other farmers in localized groups (Parks, 2022). These co-learning opportunities, as described by participant #7, were more impactful when involving one-on-one exchanges of information, knowledge, and experiences. Many participant farmers expressed the important role that "early adopters" play, either referring to themselves or other farmers in the community, as credible sources of information related to soil health. As a farmer described, early adopters are “influencing factors proving that the practice can be done and it is practical and it has worked on their operation” (Farmer #4). Another farmer said when describing one-on-one interaction with other farmers,

> “They [other farmers] will call me and ask me about certain things before they do it. Like cover crops, for instance I’ve been doing that longer than most in my neighborhood. They’ll call me to ask what kind of mix to use, timing on killing their cover crops, like the weather is right or what additives to use so that the rye dies and things like that” (Farmer #5).

Our results are in agreement with other studies showing that farmers obtain information from a variety of sources but are more open to management practices they could learn from two-way dialogue with those in their networks (Tarnoczi & Berkes, 2010).

According to interviewees, local and experiential knowledge as well as trust-building was an important component for soil health knowledge exchange (Bell, 2004; Carolan 2006). As one farmer expressed “the ones that I do talk to, is because we're both trying to accomplish the same thing. So we're trying to figure out. So it's like we're trying to help each other and learn from each other.” (Farmer #7). Many growers also expressed the importance of peer-learning groups in multiple agro-ecoregions to account for soil and climate variabilities affecting crop production. As one farmer said it,

> “I think peer learning, small local peer learning groups would be helpful. Trying to have this peer learning groups within a reasonable driving distance and in the same type of growing environment. I think in Nebraska you'd have to have more of them, probably across the state to capture the variability in the Great Plains. I think that would be a big one, and that way, farmers can learn from other farmers” (Farmer #4).

Beyond direct farmer-to-farmer connections, interactions with other agricultural stakeholders are also import on farmer’s decision to adopt soil health practices. Although co-learning opportunities involved interaction among groups with similar soil health-related motivation and beliefs as described by the quotes above, interviewees also expressed openness to listen to both sides and learn from contrasting ideas related to soil health. “You kind of got skepticism in all the groups [university, growers association, other farmers, experts]. Some of them will find things wrong with things that you think are right, and maybe they're right sometimes too” (Farmer #5)” one grower expressed. While growers generally believed cover crops would improve the health of their soils, they acknowledged that input costs, particularly expenses with cover crop seeds, might be a factor limiting other farmers’ use of them. As a farmer expressed,

> “I have gotten 5000 acre farms aside to me, and he puts cover crops on just about everything. Then I got another one, and he puts cover crops on nothing. “It's too expensive”. They both farm about that much, but one's never gotten doing, the other one is doing it. I think that you can probably get information on both sides, that doesn't pay and it does. I think if you really want information on cover crops, I think there's plenty out there” (Farmer #2).

These comments reflect participants understanding that soil health practices are context-specific and require understanding of farming goals in adopting cover crops (e.g., erosion control, nutrient, water, weed management). Such site-specific goals would determine selection of most suitable cover crop management practices such as species selection, planting and termination date and methods affecting the management practice costs.

Co-learning opportunities seem to help farmers understand the broad range of implications that soil health management decisions have on farms. Sharing with other farmers and agricultural stakeholders in the community the struggles and learnings, in other words, “what worked and what hasn't worked" (Farmer #4), with specific management decisions was echoed by farmers, more specifically two of the interviewees who had extension or consulting in addition to their farming roles. For example, issues with wheat stem maggot (*Meromyza americana* Fitch) infesting corn fields following late-terminated, or often referred to "planting green", cover crops was mentioned: "because we planted it green in the triticale, we did have wheat stem maggot move from the triticale to the corn. I've already shared that with a couple producers this year since it happened, like here's it's not always roses, right?" (Farmer # 4). Other farmer's shared reports in the same growing region have allowed further systematic research investigations and confirmation that cover crop management practices, in particularly termination timing decisions, are one of the key risk factors for this pest infestation in cover crop-based systems (Inveninato Carmona et al., 2019). Another participant farmer with extension and consulting roles demonstrated the importance of meeting other farmers where they are in their learning process by sharing

> "When you're trying to convince people of how you can do it better, it becomes very hard. But like I said, now that we've kind of switched our tactics or goal, I guess, to really meet those people where they're at, it's so much better" (Farmer # 1).

Adoption of soil health-promoting practices is positively associated with utilization of social networks (Prokopy et al., 2008). Central and trusted organizations such as land grant universities Extension can foster networking opportunities between well and less-connected farmers, particularly across ecoregions, to guide new, trusting relationships of information-exchange to develop while leveraging the existing network structure. Learnings from the SHI, a unique case of participatory form of research, also brings opportunities to rethink traditional extension and technology transfer models that privilege scientific research and information while overlooking local, experiential forms of knowledge (Pretty and Chambers, 2003).

On-Farm Experimentation

The factors supporting farmer's social and informational networks influences on sustained use of soil health practices discussed previously – land tenure, perceived acceptance, family farming tradition, and co-learning – all set the stage for on-farm experimentation (Table 5.2, Figure 5.2). During the in-depth interviews, farmers shared the perceived benefits of involving in partnerships, namely on-farm research and federal conservation programs, as it relates to their network of people and sustained adoption of soil health practices.

Expanded network

Opportunities to interact with a broader community of farmers and stakeholders, and therefore expanding farmer's network, was one of the main benefits reported by participants. The interviewee who had consulting in addition to their farming roles, shared recent interactions with out of state groups of people, namely medical professionals, interested in learning about cattle production using agro-ecological principles:

> "We've got a great local following and we've got a great following in a lot of ways here and globally, in a sense. The people that reached out were like a lot of medical professionals, a lot of people like…"So your beef is better just based on the forages, and how you're doing, and what you're not doing" (Farmer #1).

Participatory forms of research as the SHI also involve opportunities for students to be involved in the research process, interact with farmer and establish meaningful connections as described by participant #6:

> "By doing this research I've met a lot of people, you know, I would have never met you, if not for this research. My wife and I have talked a lot about when I quit doing that research, we're never going to see you guys again. I've enjoyed so much getting to know you and I hope our paths cross again someday" (Farmer # 6).

Consistent with prior research (Akkerman & Bakker, 2011; Hardie Hale et al., 2021; Wenger, 1998), alignment with institutions and networks at different scales (e.g., local, regional, and national level) is one of the factors emphasized in research on collaborative contexts.

Field days and farmer networking meeting

Participation in field days and networking meetings was another benefit farmers expressed in regards to their involvement in this on-farm research and agricultural conservation programs. In particular, farmers expressed that several of these field days attracted "late adopters" – groups of young farmers interested in learning and "giving a try" to soil health practices. As one farmer put it, "He [other farmer] was telling me that pretty well due to that field day that they were going to try that [cover crops]". But they have, they followed up on it." (Farmer #2). Another farmer shared opportunities to host field days and engage with the farming community as part of the several on-farm research projects they were part of, which includes testing winter killed and winter terminated cover crop species, short and long-season soybean maturity groups, and cover crop variety trials. As the farmer expressed,

> "I think I've had at least three field days out here. I think that would have had an influence on people, otherwise they wouldn't have come. We've had a good turnout at all the field day that we had on it. So I think it an influence on some people." (Farmer #6)

Teaching future generation of agricultural workforce

Several interviewees expressed the opinion that teaching the future generation of farmers and agricultural stakeholders, through education and outreach activities, was critical for large-scale and continued adoption of soil health practices. One farmer mentioned these education needs as a form of breaking or discontinuing some "family farming traditions". As the farmer told us,

> “A lot of the young farmers that don't believe in this [soil health], I think, they need education from the time they go to farming. Anyone that goes to college in the Ag area needs to be kind of indoctrinated into the point, into the fact that we need to save our soil. I think that might be where more good would come for the next generation. But there's a lot of them that don't go to college, they just take up farming and do the same thing their dad did. If their dad say “that's stupid”. Well, of course they aren’t going to do it, and you do have those that break away from their dad. But usually their dad has gotten the first string. So it's hard for them, somebody that goes back on the farm” (Farmer #2).

Another farmer expressed the challenge of discontinuing family-farming traditions that are not aligned with soil heath principles “Farmer are very stubborn. It's a slow process to change them “I’m not doing it and that's it. I've been doing it this way, my grandpa did it, my dad did it. I am not changing” (Farmer #3). Another interviewee with extension/consulting roles, also shared opportunities of interacting with a large group of young students and sparking in them interest for soil health:

> “I spoke at a school close to here, a larger school, 500 or 700 kids, all grade school kids. Pictures, and then me sniffing the soil, and holding soil, and all these earthworms. And I talked to them about this is what we're doing. In just a couple minutes, all these kids are shaking their head [positively] like that's cool. You can tell they knew that's exactly the way you should do it” (Farmer #1).

Considering the average age of farmers in the US is 57.5 and continues to increase (USDA-NASS 2019), beginning and young farmers represents a key group who could be leveraged to help spread information about soil health by virtue of having more connections to others (Parks, 2022).

Trial and error – adaptive management approach

Learning also involves experimentation, which is characterized as a form of trial and error on farms. As one farmer shared with us, “I’m still working through trial and error. The cover crops, there's so much to learn yet. You don't pick up a fortune magazine, and it says “this is what you need to do, and being successful”. You have to do it on your own, and you need to do it on a small scale first (Farmer #3).” Given the variety of factors influencing implementation of conservation practices, the adoption of soil health practices in agricultural settings is not straightforward process (Nowak 1987; Garbach & Long 2017). The on-farm experimentation and observation that farmer #3 described above was likely less systematic than the scientific research trials or laboratory experiments. Farming systems are complex, similarly to dynamic natural systems with multiple uncontrollable variables that ecologists and conservationists work in (Carr & Hazell 2006). So while farmers, extension personnel and conservation professionals came to work on the SHI project with distinct bodies of knowledge, the shared understanding of the importance of experimentation process (through trial and error) was important to set the stage for integrating knowledge among these groups (Hardie Hale et al., 2021).

Real-time and scientific results

Farmers also expressed the importance of on-farm research trials as more systematic experiments to obtain real time and scientific results. As one farmer expressed,

> “That’s where the extension and the NRCS was helpful because they can actually analyze the data a lot more than I could just as a layman. They have the statisticians, the scientists, you know, they can do all that. While I was looking at it just as anecdotal information, once those two organizations got involved in it was real science that was backing the results of the different types of practices” (Farmer #1).

Studies of collaborative and participatory research projects consistently report the importance of regular communication and sharing results across researchers and community partners (Shirk et al. 2012). While only one participant in our interview desired more frequent updates about the SHI project results, the farmer acknowledged the role that the COVID pandemic had on in-person meetings. We also found evidence of a lack of shared ownership in some parts of the process, which is not atypical in collaborative forms of research (Hardie Hale et al., 2021). For example, farmer 3 expressed frustration that they wish to have received more results and that the project "left as many questions as the farmer had before project started". The majority of on-farm experiments are employed to provide in-situ validation, as a demonstration purpose, or service purchased by farmers, which limits the power of agricultural experimentation in rediscovering the multidimensional ramifications of inspiration, ideation and implementation for problem-solving (Lacoste et al., 2022). Thus, farmer's sense of ownership and connection to the process might have been strengthened if more regular opportunities were provided for farmers to understand on-farm experimentation as a powerful pragmatic process to generate further research questions.

Objective 2

Describe Social Networks Impact on Farmers' Decision Making and Their Priority Ranking of Candidate Management Practice to Improve Soil Health

The annual meetings promoted by the UNL On-Farm Research network was an important vehicle to present the SHI annual report and project results to a broader community of farmers and stakeholders. During the interactive activity deployed as part of the 2020 annual meeting, farmers ranked several groups of people impact on their overall and soil-health related farming decision making. Figure 5.3 illustrates the priority ranking of each group among participants. Family member or farm partner (mean response of 2.0/5 for overall decisions and 2.7/5 for soil health decisions), other farmers on the community (mean response of 3.1/5 for overall and 3.3/5 for soil health decisions), crop advisor/consultant (means response of 2.3/5 overall and 2.8/5 for soil health decisions), university extension (mean response of 2.7/5 overall and 2.5/5 for soil health decisions), and conservationists within NRCS (mean response of 2.9/5 for overall and 2.5/5 for soil health decisions) were the groups with the greatest impact on farmer's both overall decision making as well as decisions related to soil health (Figure 5.2, Figure 5.3). The second activity focused on practices that extension personnel, NRCS conservationists and certified professional advisers perceived to have the greatest impact on soil health were most willing to recommend to farmers. Figure 5.4 illustrates the priority ranking of each management among participants. No-till (mean response of 1.3/5 for practice impact and 1.2/5 for practice recommendation) and cover crops (mean response of 1.5/5 for practice impact and 1.8/5 for practice recommendation) were the practices ranked as both greatest impact on soil health and most likely to be recommended to farmer.

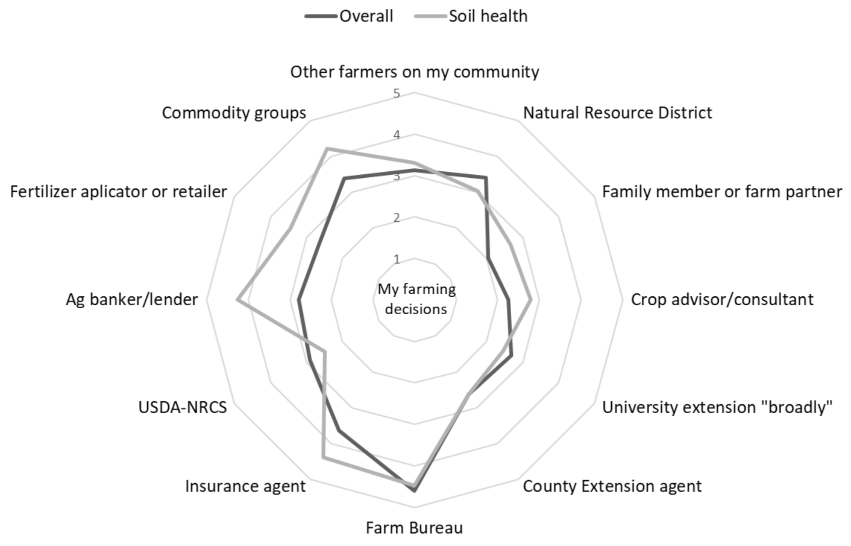

Figure 5.3. Farmer (n=30) evaluation of people or groups impact on their overall and farming decisions related to soil health. Score closer to one (center of the grid) indicates groups viewed as having a larger impact whereas score closer to five (towards the outer edge of the grid) indicates groups viewed as having lesser impact on farmer's decision making.

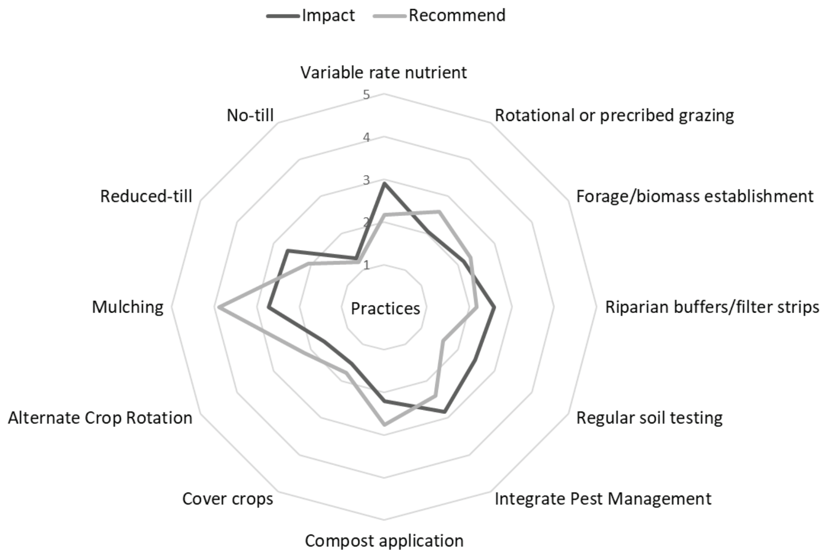

Figure 5.4. Extension personnel, conservationists and crop advisors (n=19) evaluation of the impact of management practices on improving soil health and their willingness to recommend the practices to a farmer. Score closer to one (the center of the grid) indicates practices viewed as having a larger impact on soil health or more likely to recommend. Score closer to five (towards the outer edge of the grid) indicates practices having lesser impact or less likely to recommend.

Consistent with prior research (Eanes et al., 2019), certified professional advisers held positive attitudes towards soil health promoting practices, particularly cover crops and no-tillage in our study, and were willing to facilitate practice adoption by recommending them to their clientele. Interaction with agricultural advisors and other farmers coupled with trust in different information sources influence farmer's climate change beliefs and adaptation strategies, which involves adoption of soil health practices (Arbuckle et al., 2015; Roesch-McNally et al., 2018; Prokopy et al., 2015). Farmers' knowledge on soil health is a social relation that only comes about through interactions with trusted sources (Bell, 2004). Thus, understanding the role that these "intermediaries" play on farmers' decision making is critical for leveraging networks of trusted, on-farm professionals to meet both informational and technical assistance needed related to soil health. These include, but are not limited to, cooperative Extension and USDA's NRCS employees working alongside certified professional advisers (e.g., certified crop and professional soil advisors) to bring the latest soil health information, techniques, and technologies to farmers.

Objective 3

Describe Learnings from Five-Year On-Farm Experimentation on Soil Health Management

Multiple soil and agronomic responses that indicate improvements in soil health were documented as part of the SHI 5-year demonstration projects (Table 5.3). This includes findings on how cover crops impact soil properties and crop performance (i.e., yields) at the farm scale. Briefly, cover crops resulted on neutral impacts on subsequent corn, soybean, and small grain yields on most of the farm-year comparisons, but some positive and or negative yield impacts were also documented (Table 5.3). Table 5.3 also show the impact of soil management comparisons on soil health, which was assessed considering properties such as infiltration, soil moisture, bulk density, soil temperature, soil respiration as well as a soil health score based on visual inspection. In general, we observed either neutral or positive impacts of management comparisons on soil health across the five-year experimentation.

Farmers' behavioral persistence towards soil health practices beyond the spatial and temporal scope of conservation incentive programs is highly important for long-term agricultural sustainability goals. By using a farmer-initiated approach to on-farm experimentation, research questions on conservation practices are generated by the farmers based on natural resource (e.g., soil) concerns and their management goals (Ranjan, 2020). This provides farmers experiential learning opportunities in the environment where management practices possibly would be implemented, which is seen as an effective way to encourage voluntary behavior change among farmers (Dayer et al., 2018). Many changes in physical, chemical, and biological soil properties, as well as agronomic responses, that indicate improvements in soil health, are complex and variable as shown in our results (Table 5.3). For example, soil aggregate stability, infiltration rates, and microbial indicators quantified by meta-analysis are shown to be very responsive (1-3 years for changes detection) to changes in cover crop and no-tillage adoption (Steward et al., 2018). However, other soil properties, such as organic carbon accumulation, might take over five years to detect significant changes due to management interventions that reverse soil degradation (Angers & Eriksen-Hamel, 2008). Thus, farmers commitment to continue soil health management practices after incentive program or on-farm research ends is critical, given many of the soil health-promoting practices accumulate benefits relatively slowly over time.

Table 5.3. Summary table yield and soil health impacts of management comparisons conducted as part of the soil health initiative 5-year demonstration projects. For detailed information and report, please consult Nebraska Extension On-Farm Research (2021).

County location	Management comparison	5-year summary yield impact	5-year summary soil health impact
Nemaha County	Winter terminated vs winter hardy cover crops	Neutral or negative effects of winter hardy cover crop on corn/soybean yield; Delayed growth/development in corn/soybean following winter hardy cover crops	No differences in soil health indicators between management comparisons[1]
Greeley County	Cover crop mix vs check (no cover crop)	Neutral effect of cover crop mix on soybean and small grain yield	Higher soil health score in the cover crop treatment areas[2]
Stanton County	Cereal rye cover crop vs multi-species cover crop mix	Neutral effect of rye or multi-species cover crop mix on corn and small grain yield; Positive effect of multi-species cover crop mix on soybean yield	Higher soil health scores in single species treatment areas, and trends of increases in infiltration rate and decreases in bulk density over time for both management
Merrick County	Dormant (post-harvest) vs. interseeded cover crop vs check (no cover crop)	Neutral effect of interseeded cover crop on corn yield.	Higher soil health score in the cover crop (both dormant and interseeded) areas
Howard County	Cover crop mix vs check (no cover crop)	Neutral effect of cover crop mix on corn, soybean, and small grain yield.	Higher soil health score in cover crop treatment areas, and trends of increase in infiltration rates and soil health score over time in cover crop treatment areas.
Dodge County	Corn/soybean vs corn/soybean/small grain rotation with cover crop	Neutral or negative effects of small grain rotation on soybean yield; Positive or neutral effect of small grain rotation on corn yield.	Trends of higher infiltration rate and soil health score over time for both management.
Colfax County	Cover crop mix vs check (no cover crop)	Neutral or negative effects of cover crop mix on corn, soybean and small grain yield.	Trends of higher soil health score over time for both management.

[1] Infiltration, soil moisture, bulk density, soil temperature, soil respiration (Modified Solvita burst), soil health score.

[2] Score based on field assessment. The overall indicator score is based on the sum of 8 indicators (1=degraded, 2=in transition, 3=healthy): soil structure, structure type, surface condition, soil management, soil pores, earthworms, biological activity, and smell.

The annual Nebraska On-Farm Research Network meetings were an important vehicle to present the results summarized in Table 5.3 to a broader community of farmers and stakeholders. Post-event survey results from the 2020 and 2021 annual meeting impact reports included 77% participant agreement for the statements "As a result of today's educational opportunity, I have a better understanding of cover crop management" and "I learned new information about cover crops" (Table 5.4). To the extent that this collaboratively designed on-farm research provided farmers with an improved understanding of the benefits of more environmentally sound management practices that embody the principles of soil health (e.g., maximize biodiversity, soil cover and continuous living roots and minimizing soil disturbance), experiences with this partnership could translate into farming benefits in the long run as farmers are better able to adapt management practices to individual farming operations.

Table 5.4. Summary of 2020 and 2021 impact reports from post-event survey annual meetings promoted by the On-Farm Research Network.

Survey statement	Strongly disagree % (count)	Disagree % (count)	Agree % (count)	Strongly agree % (count)
I learned new information about cover crops	1% (2)	15% (20)	77% (100)	7% (10)
As a results of today's educational opportunity, I have a better understanding of cover crop management	1% (2)	15% (19)	77% (100)	7% (9)
I feel that I have a pretty good understanding of the principles of soil health	0% (0)	11% (5)	73% (33)	16% (7)
I feel that I am better informed about the principles of soil health than most farmers	2% (1)	12% (5)	74 % (32)	12% (5)
When receiving information about soil health, I like to gather as much information as possible	0% (0)	4% (2)	73% (33)	22% (10)
When receiving information about soil health, I like to learn from all sources	0% (0)	2% (1)	66% (29)	32% (14)

Conclusions

Partnering federal conservation initiatives with land-grant university extension programming provides unique learning and network opportunities among project partners. From an agricultural sustainability perspective, farmer conservation behavior persistence beyond the spatial and temporal scope of on-farm research experimentation and conservation incentive programs is desirable. Yet, the drivers of sustained use of soil health practices, in part influenced by farmers' social networks and sources of information, are often overlooked. Our study contributed to an understanding of how farmer's social and informational networks influenced sustained adoption of soil health practices, providing recommendations for both practice and research.

Recommendations for Practice

Insights about the factors supporting or facilitating sustained behavior could provide important guidelines for practitioners seeking to leverage network of stakeholders to meet informational, social, and technical assistance needed related to soil health. For example, agricultural entities working on outreach programs may consider prioritizing peer-groups or roundtable discussions instead of a one-way delivery of information methods (e.g., lectures, webinars). Another way to encourage sustained behavior as part of farmer's management plans is to ensure landowners and tenants are equipped to initiate conservations about soil health practices. One example could be the creation of publication series "Talking with your landowner and tenant" including responses to commonly asked questions on how to maneuver communication between the two parties in regards to soil health management. Additionally, research and extension programming should seek for opportunities to integrate beginning farmers as part of the research process by conducting multi-year and multi-location on-farm coupled with small plot-scale research.

Recommendations for Research

Future research should replicate this study at other states to better understand how social and informational network influence farmers sustained use of soil health management. Additionally, using a mixed-methods approach and collecting quantitative data to create network maps of participants involved in on-farm research and conservation programs would help to generalize the findings and make the research more robust. This study focused on farmers' part of on-farm research couple with financial incentive program, but there is an opportunity to explore groups of farmers who are not engaged in these initiatives. Specifically, farmers who are currently non-adopters of soil health management who could help to understand other network structures as well as main barriers preventing them to adopt and sustain management practices.

In summary, those are some strategies, among many, needed to initiate and maintain soil health practice adoption in privately managed land. Our findings and recommendations reflect those corn and soybean grain farmers and stakeholders in the Nebraska who were part of the NRCS Soil Health Initiative in collaboration with the Nebraska On-Farm Research Network. This study provided an effective lens to better understand social and information network influences on farmer's behavioral persistence related to soil health. However, the broad applicability of our proposed strategies should be further examined in agricultural systems.

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References

Akerlof, K., & Kennedy, C. (2013). Nudging toward a healthy environment: How behavioral change research can inform conservation. *White paper for the Gordon and Betty Moore Foundation*. George Mason University, Fairfax, VA.

Akkerman, S. F., & Bakker, A. (2011). Boundary crossing and boundary objects. *Review of educational research*, *81*(2), 132-169.

Arbuckle Jr, J. G., Morton, L. W., & Hobbs, J. (2015). Understanding farmer perspectives on climate change adaptation and mitigation: The roles of trust in sources of climate information, climate change beliefs, and perceived risk. *Environment and behavior*, *47*(2), 205-234.

Armitage, D. R., Plummer, R., Berkes, F., Arthur, R. I., Charles, A. T., Davidson-Hunt, I. J., ... & Wollenberg, E. K. (2009). Adaptive co-management for social–ecological complexity. *Frontiers in Ecology and the Environment*, *7*(2), 95-102.

Barnett, M. J., Spangler, K., Petrzelka, P., & Filipiak, J. (2020). Power dynamics of the non-operating landowner-renter relationship and conservation decision-making in the midwestern United States. *Journal of Rural Studies*, *78*, 107-114.

Basche, A., & Carter, A. (2021). Training future agriculture professionals in landowner–tenant conservation decision-making. *Natural Sciences Education*, *50*(1), e20035.

Basche, A., Tully, K., Álvarez-Berríos, N. L., Reyes, J., Lengnick, L., Brown, T., ... & Roesch-McNally, G. (2020). Evaluating the untapped potential of US conservation investments to improve soil and environmental health. *Frontiers in Sustainable Food Systems*, *4*, 236.

Baumgart-Getz, A., Prokopy, L. S., & Floress, K. (2012). Why farmers adopt best management practice in the United States: A meta-analysis of the adoption literature. *Journal of environmental management*, *96*(1), 17-25.

Belknap, J., & Saupe, W. E. (1988). Farm family resources and the adoption of no-plow tillage in Southwestern Wisconsin. *North Central Journal of Agricultural Economics*, *10*(1), 13-23.

Bell, M. M. (2010). *Farming for us all: Practical agriculture and the cultivation of sustainability*. University Park, PA: Pennsylvania State University Press.

Birks, M., & Mills, J. E. (2015). *Grounded theory: A practical guide* (2nd ed.). Los Angeles, CA: Sage.

Buck, H. J., & Palumbo-Compton, A. (2022). Soil carbon sequestration as a climate strategy: what do farmers think?. *Biogeochemistry*, *161*(1), 59-70.

Burkholder, G. J., Cox, K. A., Crawford, L. M., & Hitchcock, J. H. (Eds.). (2019). *Research design and methods: An applied guide for the scholar-practitioner*. SAGE Publications.

Carolan, M. S. (2006). Social change and the adoption and adaptation of knowledge claims: Whose truth do you trust in regard to sustainable agriculture?. *Agriculture and human values*, *23*, 325-339.

Carr, A., & Hazell, D. (2006). Talking frogs: the role of communication in ecological research on private land. *Biodiversity & Conservation*, *15*(10), 3177-3191.

Carlisle, L., Esquivel, K., Baur, P., Ichikawa, N. F., Olimpi, E. M., Ory, J., ... & Bowles, T. M. (2022). Organic farmers face persistent barriers to adopting diversification practices in California’s Central Coast. *Agroecology and Sustainable Food Systems*, *46*(8), 1145-1172.

Charmaz, K. (2014). *Constructing grounded theory* (2nd ed.). London: Sage.

Chapman, M., Wiltshire, S., Baur, P., Bowles, T., Carlisle, L., Castillo, F., ... & Boettiger, C. (2022). Social-ecological feedbacks drive tipping points in farming system diversification. *One Earth*, *5*(3), 283-292. https://doi.org/10.1016/j.oneear.2022.02.007

Church, S. P., & Prokopy, L. S. (2017). The influence of social criteria in mobilizing watershed conservation efforts: A case study of a successful watershed in the Midwestern US. *Land Use Policy*, *61*, 353-367.

Creswell, J. W. (2013). *Qualitative inquiry & research design: Choosing among five approaches* (3rd ed.). Thousand Oaks, CA: Sage.

CRS (2018). 2018 Farm Bill Primer: What Is the Farm Bill?. Congressional Research Service. Available online at: https://crsreports.congress.gov/product/pdf/IF/IF11126 (accessed February 13, 2023).

CRS (2019). Agricultural Conservation: A Guide to Programs. Congressional Research Service. Available online at: https://crsreports.congress.gov/product/pdf/R/R40763 (accessed February 13, 2023).

Crotty, M. (1989). *The foundations of social research: Meaning and perspective in the research process.* London: SAGE.

Czap, N. V., Czap, H. J., Banerjee, S., & Burbach, M. E. (2019). Encouraging farmers' participation in the Conservation Stewardship Program: A field experiment. *Ecological economics*, 161, 130-143.

Czap, N. V., Czap, H. J., Khachaturyan, M., Burbach, M. E., & Lynne, G. D. (2018). Experiments on empathy conservation: Implications for environmental policy. *Journal of Behavioral Economics for Policy*, 2, 71-77.

Dayer, A. A., Lutter, S. H., Sesser, K. A., Hickey, C. M., & Gardali, T. (2018). Private landowner conservation behavior following participation in voluntary incentive programs: Recommendations to facilitate behavioral persistence. *Conservation Letters*, *11*(2), e12394.

Eanes, F. R., Singh, A. S., Bulla, B. R., Ranjan, P., Fales, M., Wickerham, B., Doran, P. J., & Prokopy, L. S. (2019). Crop advisers as conservation intermediaries: Perceptions and policy implications for relying on nontraditional partners to increase US farmers' adoption of soil and water conservation practices. *Land use policy*, 81, 360-370.

Evans, D. L., Quinton, J. N., Davies, J. A., Zhao, J., & Govers, G. (2020). Soil lifespans and how they can be extended by land use and management change. *Environmental Research Letters*, *15*(9), 0940b2.

Floress, K. M., Gao, Y., Gramig, B. M., Arbuckle, J. G., Church, S. P., Eanes, F. R., Ranjan, P., Singh, A. S., & Prokopy, L. S. (2019). Meta-analytic data from agricultural conservation practice adoption research in the United States 1982-2018. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2019-0011.

Floress, K., Reimer, A., Thompson, A., Burbach, M., Knutson, C., Prokopy, L., ... & Ulrich-Schad, J. (2018). Measuring farmer conservation behaviors: Challenges and best practices. *Land use policy*, 70, 414-418.

Folke, C., Hahn, T., Olsson, P., & Norberg, J. (2005). Adaptive governance of social-ecological systems. *Annu. Rev. Environ. Resour.*, *30*, 441-473.

Garbach, K., & Long, R. F. (2017). Determinants of field edge habitat restoration on farms in California's Sacramento Valley. *Journal of Environmental Management*, *189*, 134-141.

Givens, W. A., Shaw, D. R., Kruger, G. R., Johnson, W. G., Weller, S. C., Young, B. G., ... & Jordan, D. (2009). Survey of tillage trends following the adoption of glyphosate-resistant crops. *Weed technology*, *23*(1), 150-155. https://doi. org/10.1614/WT-08-038.1.

Hardie Hale, E., Jadallah, C. C., & Ballard, H. L. (2022). Collaborative research as boundary work: learning between rice growers and conservation professionals to support habitat conservation on private lands. *Agriculture and Human Values*, *39*(2), 715-731.

Hiller, T. L., Powell, L. A., McCoy, T. D., & Lusk, J. J. (2009). Long-term agricultural land-use trends in Nebraska, 1866—2007. *Great Plains Research*, 225-237.

Inveninato Carmona, G., Rees, J., Seymour, R., Wright, R., & McMechan, A. J. (2019). Wheat stem maggot (Diptera: Chloropidae): an emerging pest of cover crop to corn transition systems. *Plant Health Progress*, *20*(3), 147-154. https://doi.org/10.1094/PHP-01-19-0009-S

Kim, S., Gillespie, J. M., & Paudel, K. P. (2005). The effect of socioeconomic factors on the adoption of best management practices in beef cattle production. *Journal of Soil and Water Conservation*, *60*(3), 111-120.

Kladivko, E. J., Holscher, L., Boyle-Warner, J., Fisher, B., Rorick, J. D., & Zuber, S. M. (2019). State-wide soil health programs for education and on-farm assessment: Lessons learned. *Journal of Soil and Water Conservation*, *74*(1), 12A-17A.

Knowler, D., & Bradshaw, B. (2007). Farmers' adoption of conservation agriculture: A review and synthesis of recent research. *Food policy*, *32*(1), 25-48.

Krupek, F. S., Redfearn, D., Eskridge, K. M., & Basche, A. (2022a). Ecological intensification with soil health practices demonstrates positive impacts on multiple soil properties: A large-scale farmer-led experiment. *Geoderma*, *409*, 115594. https://doi.org/10.1016/j.geoderma.2021.115594.

Krupek, F. S., Mizero, S. M., Redfearn, D., & Basche, A. (2022b). Assessing how cover crops close the soil health gap in on-farm experiments. *Agricultural & Environmental Letters*, *7*(2), e20088. https://doi.org/10.1002/ael2.20088

Lacoste, M., Cook, S., McNee, M., Gale, D., Ingram, J., Bellon-Maurel, V., ... & Hall, A. (2022). On-Farm Experimentation to transform global agriculture. *Nature Food*, *3*(1), 11-18.

Merriam, S. (1988). *Case study research in education: A qualitative approach*. San Francisco, CA: Jossey-Bass.

Merriam, S. B., & Tisdell, E. J. (2016). *Qualitative research: A guide to design and implementation* (4th ed.). San Francisco, CA: John Wiley & Sons.

Moore, E. A., & Koontz, T. M. (2003). Research note a typology of collaborative watershed groups: Citizen-based, agency-based, and mixed partnerships. *Society &Natural Resources*, *16*(5), 451-460.

Nebraska Extension On-Farm Research, 2021. Cover crop studies. In 2021 on-farm research results (pp. 142–182). Available at: https://on-farm-research.unl.edu/pdfs/research/result-publications/2021research-results.pdf (accessed February 13, 2023).

Nowak, P.J. 1987. The adoption of agricultural conservation technologies: Economic and diffusion explanations. *Rural Sociology* 52 (2): 208.

Pahl-Wostl, C., & Hare, M. (2004). Processes of social learning in integrated resources management. *Journal of community & applied social psychology*, *14*(3), 193-206.

Parks, M. (2022). Exploring the influence of social and informational networks on small farmers' responses to climate change in Oregon. *Agriculture and Human Values*, *39*(4), 1407-1419.

Pretty, J., & R. Chambers. (2003). Towards a learning paradigm: new professionalism and institutions for agriculture. In *Rethinking sustainability: Power, knowledge, and institutions*, ed. J. Harris. Ann Arbor, MI: University of Michigan Press.

Prokopy, L. S., Arbuckle, J. G., Barnes, A. P., Haden, V. R., Hogan, A., Niles, M. T., & Tyndall, J. (2015). Farmers and climate change: A cross-national comparison of beliefs and risk perceptions in high-income countries. *Environmental management*, *56*, 492-504.

Prokopy, L. S., Floress, K., Arbuckle, J. G., Church, S. P., Eanes, F. R., Gao, Y., Ranjan, P., & Singh, A. S. (2019). Adoption of agricultural conservation practices in the United States: Evidence from 35 years of quantitative literature. *Journal of Soil and Water Conservation*, 74(5), 520-534.

Prokopy, L. S., Floress, K., Klotthor-Weinkauf, D., & Baumgart-Getz, A. (2008). Determinants of agricultural best management practice adoption: Evidence from the literature. *Journal of soil and water conservation*, *63*(5), 300-311.

Reimer, A. P., & Prokopy, L. S. (2012). Environmental attitudes and drift reduction behavior among commercial pesticide applicators in a US agricultural landscape. *Journal of environmental management*, *113*, 361-369.

Roesch-McNally, G. E., Basche, A. D., Arbuckle, J. G., Tyndall, J. C., Miguez, F. E., Bowman, T., & Clay, R. (2018). The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. *Renewable Agriculture and Food Systems*, *33*(4), 322-333.

Rogers, E. M. (2003). *Diffusion of innovations*. New York, NY: Simon & Schuster.

SARE-CTIC, 2020, 2019-2020 Cover Crop Survey North Central Sustainable Agriculture Research & Education - Conservation Technology Information Center. Available at https://www.ctic.org/files/CoverCropSurvey%202020%2024mb.pdf (accessed February 15, 2023).

Soil for climate (2019). Healthy soils legislation update. Available at https://www.soil4climate.org/news/healthy-soils-legislation-update-may-2019 (accessed February 13, 2023).

Stake, R. (1995). *The art of case study research*. Thousand Oaks, CA: Sage.

Stern, M.J. (2018). Social Science Theory for Environmental Sustainability: A Practical Guide. Oxford: Oxford University Press.

Stern, P. C., Dietz, T., Abel, T., Guagnano, G. A., & Kalof, L. (1999). A value-belief-norm theory of support for social movements: The case of environmentalism. *Human ecology review*, 81-97.

Stewart, R. D., Jian, J., Gyawali, A. J., Thomason, W. E., Badgley, B. D., Reiter, M. S., & Strickland, M. S. (2018). What we talk about when we talk about soil health. *Agricultural & Environmental Letters*, *3*(1).

Tarnoczi, T. J., & Berkes, F. (2010). Sources of information for farmers' adaptation practices in Canada's Prairie agro-ecosystem: A letter. *Climatic change*, *98*(1-2), 299.

Thompson, A. W., Reimer, A., & Prokopy, L. S. (2015). Farmers' views of the environment: the influence of competing attitude frames on landscape conservation efforts. *Agriculture and human values*, *32*, 385-399.

Thompson, L. J., Glewen, K. L., Elmore, R. W., Rees, J., Pokal, S., & Hitt, B. D. (2019). Farmers as researchers: in-depth interviews to discern participant motivation and impact. *Agronomy Journal*, *111*(6), 2670-2680.

U.S. Congress (2019). The 116th Congress - S.2452 Climate Stewardship Act. Available at: https://www.govtrack.us/congress/bills/116/s2452/text (accessed February 13, 2023).

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA-NASS). (2014). Tenure, ownership, and transition of agricultural land survey. Washington, DC: National Agricultural Statistics Service. Available at https://www.nass.usda.gov/Publications/Highlights/2015/TOTAL_Highlights.pdf (accessed February 14, 2023).

USDA-NASS (2019). Farm producers. 2017 Census of Agriculture Highlights. Available at https://www.nass.usda.gov/Publications/Highlights/2019/2017Census_Farm_Producers.pdf (Accessed 15 February 2023)

Valente, T., & Davis, R. (1999). Accelerating the diffusion of innovations using opinion leaders. *Annals of the American Academy of Political and Social Science*, 566, 55-67. https://doi.org/10.1177/000271629956600105

Wander, M. M., Cihacek, L. J., Coyne, M., Drijber, R. A., Grossman, J. M., Gutknecht, J. L., ... & Turco, R. F. (2019). Developments in agricultural soil quality and health: Reflections by the research committee on soil organic matter management. *Frontiers in environmental science*, *7*, 109.

Wenger, E. (1998). *Communities of practice: Learning, meaning, and identity*. New York: Cambridge University Press.

Wick, A. F., Haley, J., Gasch, C., Wehlander, T., Briese, L., & Samson-Liebig, S. (2019). Network-based approaches for soil health research and extension programming in North Dakota, USA. *Soil use and management*, 35(1), 177-184.

Wolf, S. A., & Ghosh, R. (2020). A practice-centered analysis of environmental accounting standards: integrating agriculture into carbon governance. *Land use policy*, *96*, 103552. https://doi.org/10.1016/j.landusepol.2018.08.003

Wood, B. A., Blair, H. T., Gray, D. I., Kemp, P. D., Kenyon, P. R., Morris, S. T., & Sewell, A. M. (2014). Agricultural science in the wild: A social network analysis of farmer knowledge exchange. *PloS one*, 9(8).

CHAPTER 6 : SUMMARY AND GENERAL CONCLUSIONS

The overall objective of this dissertation research was to explore soil and human dimension considerations to design farming systems for sustaining soil health management in Nebraska. These projects quantified the impact of soil management on physical, chemical and biological properties from farm-available soil health assessments, cash crop yields, and soil organic matter in cover crop-based systems in the context of a conservation incentive and on-farm research program. Further, farmers' continued use of soil health management beyond spatial and temporal scope of their participation in collaboratively designed on-farm trials was examined through qualitative research. The range of scientific methods used in this work - from lab-based experiments to on-farm research to farmer interviews - aimed to advance scientific understanding of how to soil management practices impact soil-crop outcomes and how farmer's social networks impact their sustaining soil health management decision-making.

Chapter two found that cover crops had the most weight on driving changes in soil properties, in particular those closely related to organic matter (SOM) and carbon (C) and nitrogen (N) dynamics. The study also highlighted that when organic N pools are considered in fertilizer recommendations from commercial soil testing, there is potential for synthetic fertilizer and economic savings from improved soil biological activity via longer cover crop use - something continually reported by advanced farmers (SARE-CTIC, 2020, 2017, 2016). Chapter three found that cover crops improve physical, chemical and biological properties relative to reference soils in the short (3 yrs.) timescale, but on-farm research experiments must be sampled intentionally. Chapter four found that when cover crops are managed as they generally are as part of conservation incentive programs in the Midwest cropping systems, changes on ecologically meaningful SOM fractions is less pronounced in the short term. The study also demonstrated the potential of reference sites embodying soil health principles (e.g., maximize biodiversity, minimize soil disturbance, and maximize soil cover and continuous living roots) as an approach to agroecosystem design for improved SOM C and N dynamics and related soil functions. Chapter five found that network-based approaches that consider factors such as land tenure, perceived acceptance, family farming traditions, co-learning, and on-farm experimentation and adaptive management are important for sustaining soil health management.

Future endeavors to advance soil health research and outreach program

This research demonstrated opportunities to integrate soil health research and outreach programming. Two main areas can stem from this work, the first being advancements of soil health in research settings (i.e., experimental data) and the second on extension (i.e., science-based engagement programs).

Advancing soil health measurements and topics in the research settings

It is important for the research community to embrace soil health not as a property to measure or monitor, but as an overarching principle that is aligned with sustainability goals (Lehmann et al., 2020). This requires shifting from simply measuring and monitoring soil health towards more tangible connections with on-farm outcomes such as input use efficiency (e.g., fertilizer, water, pesticide). Additionally, soil health concept has been applied most widely to row crop production and agronomic systems in rural areas (i.e., soil fertility oriented). Soil health of urban soils has not yet received sufficient recognition, particularly research at the intersection of food production, soil health, and human health (Li et al., 2018). For example, many gardeners and urban farmers may be trying to work in areas where previous buildings were demolished, resulting in detrimental soil characteristics. Due to soil contamination and poor soil health, these land spaces are not desired for a traditional farm setting. Therefore, understanding the cost and benefits of rehabilitating soils with soil-health promoting practices is an important tool for promoting multifunctional urban landscapes (Li et al., 2018; Kadam et al., 2008). In my upcoming position, I plan to explore the cost and benefits of rehabilitating soils through management practices such as crop rotation, cover crops, inter-cropping, no-till, incorporation of perennials, soil amendments (e.g., biochar), and high habitat diversification. Another future research would be expanding the current understanding of carbon and nitrogen dynamics within soil organic matter pools of distinct ecological relevance. For example, by exploring ways to expand markets for soil health-building practices by measuring, monitoring, and verifying carbon and nutrient dynamics along with greenhouse gas emissions from a cohort of urban and peri-urban farms. There also exists a critical need to expand the co-benefits analysis of soil health toward food quality by identifying crop nutritional profile (Montgomery et al., 2022) and suppression of soil-born plant disease (Schlatter et al., 2017) affecting taste, food storage, and preparation.

Advancing soil health measurements and topics within Extension

Applied research integrated with extension has become narrowly focused on the production of the most commercially valuable or commodity crops rather than on diversified and alternative cropping systems intended to build soil health. Therefore, more participatory on-farm research is required to build soil health knowledge capacity. With increased on-farm research on soil health, farmer-to-farmers mentoring programs supported by Extension are important to strengthen the soil health knowledge and diffusion of innovation.

Soil health is context dependent. Therefore, soil-health-related engagement programs should take into account that each soil-health goal requires a specific set of parameters to be measured and monitored. For example, managing soil health for climate-change mitigation should prioritize parameters such as aggregation, water storage, organic carbon fractions, soil nitrogen forms to provide information about potential greenhouse gas emissions, including nitrous oxide. In the context of soil health water quality assessment should prioritize properties such as microbial biomass and activity, mobile nutrients, heavy-metal toxins, total organic carbon, aggregate stability, and infiltration. Finally, soil health assessment for plant production should prioritize N-mineralizing enzyme activity, aggregation, infiltration, and earthworm abundance (Lehmann et al., 2020).

To be an effective actor in soil health, it is important for Extension to build capacity not only aiming to deliver scientific soil health information tailored to farmers' unique circumstances, but also adapt its approach to community engagement by 1) recognizing existing knowledge and strength on soil health, 2) engaging in reciprocal partnership and participatory processes, and 3) being open to engaging with social, cultural, political and economic issues that challenge and motivate adoption of soil health practices. For example, I have interacted with many individuals or groups in the Corn Belt more broadly that can be sometimes skeptical in regards to the use of soil health practices. However, I understand that many individuals or groups (e.g., for example urban farmers, community gardeners, and women landowners) are already eager about soil health and incredibly adept at utilizing agroecological practices in the built environment. Therefore, it is important for extension to expand access to underserved communities, building new connections with university extension to shape soil health research and outreach directions.

Even though the conceptualization of soil health varies across farmers, policymakers, and agricultural research communities (Wade et al., 2021), the paradigm of soil health can unite these populations. Describing the mental models of soil health within and across groups of stakeholders such as the general public is important for effective science communication. When considering soil health as a communication and framing tool, it is also important to consider whether communicating the concept of soil health to the general public could drive further reformulation by the food industry by encouraging consumer demand for soil health-promoting practices. Additionally, because soil health offers a “multi-win” approach to sustainable agroecosystem management, multi and interdisciplinary educational background is required to conduct soil health-related research and outreach. Therefore, targeted training opportunities within extension on conducting multi-year trans and interdisciplinary research on soil health is critical for aspiring students, academic staff, and extension personnel to share soil health research and educational approaches.

Reference

Allen, D. E., Singh, B. P., & Dalal, R. C. (2011). Soil health indicators under climate change: a review of current knowledge. *Soil health and climate change*, 25-45. https://doi.org/10.1007/978-3-642-20256-8_2

Basche, A., & Carter, A. (2021). Training future agriculture professionals in landowner–tenant conservation decision-making. *Natural Sciences Education*, *50*(1), e20035. https://doi.org/10.1002/nse2.20035

Kadam, A. M., Oza, G. H., Nemade, P. D., & Shankar, H. S. (2008). Pathogen removal from municipal wastewater in constructed soil filter. *Ecological Engineering*, *33*(1), 37-44. https://doi.org/10.1016/j.ecoleng.2007.12.001

Lehmann, J., Bossio, D. A., Kögel-Knabner, I., & Rillig, M. C. (2020). The concept and future prospects of soil health. *Nature Reviews Earth & Environment*, *1*(10), 544-553. https://doi.org/10.1038/s43017-020-0080-8

Li, G., Sun, G. X., Ren, Y., Luo, X. S., & Zhu, Y. G. (2018). Urban soil and human health: a review. *European Journal of Soil Science*, *69*(1), 196-215. https://doi.org/10.1111/ejss.12518

Montgomery, D. R., Biklé, A., Archuleta, R., Brown, P., & Jordan, J. (2022). Soil health and nutrient density: preliminary comparison of regenerative and conventional farming. *PeerJ*, *10*, e12848.

SARE-CTIC, 2016, 2015-2016 Cover Crop Survey North Central Sustainable Agriculture Research & Education - Conservation Technology Information Center. https://www.sare.org/wp-content/uploads/2015-2016-Cover-Crop-Survey-Report.pdf

SARE-CTIC, 2017, 2016-2017 Cover Crop Survey North Central Sustainable Agriculture Research & Education - Conservation Technology Information Center. https://www.sare.org/wp-content/uploads/2016-2017-Cover-Crop-Survey-Report.pdf

SARE-CTIC, 2020, 2019-2020 Cover Crop Survey North Central Sustainable Agriculture Research & Education - Conservation Technology Information Center. https://www.sare.org/wp-content/uploads/2019-2020-National-Cover-Crop-Survey.pdf

Schlatter, D., Kinkel, L., Thomashow, L., Weller, D., & Paulitz, T. (2017). Disease suppressive soils: new insights from the soil microbiome. *Phytopathology*, *107*(11), 1284-1297. https://doi.org/10.1094/PHYTO-03-17-0111-RVW

Wade, J., Beetstra, M. A., Hamilton, M. L., Culman, S. W., & Margenot, A. J. (2021). Soil health conceptualization differs across key stakeholder groups in the Midwest. *Journal of Soil and Water Conservation*, *76*(6), 527-533. https://doi.org/10.2489/jswc.2021.02158

APPENDIX 1 SUPPEMENTARY MATERIAL CHAPTER 2

Table S1. Soil management history of the ten farm counties included in this study.

Farm county	Soil order	Cash crop in 2019	Years of cover crop use	Cash crop sequence 2019--2015[1]	SH management treatments 2016/2017---2021/2022[2]	Years without soil disturbance	Grazing component 2019--2015[3]	Organic amendment 2019--2015
Greeley	Entisols and Alfisols	Soy	0	Soy/Mze/Soy/Mze/Soy + rye	no CC	10	Y _ _N N	N _ _ _ _
Greeley		Soy	4	Soy + CC/Mze + CC/Soy + CC/Mze + CC/Soy + rye	CC mixture (5)	10	Y _ _N N	N _ _ _ _
Howard	Mollisols	Soy	0	Soy/Mze/Soy/Mze + Rye	no CC	0	N _ _ _	N _ _ _
Howard		Soy	0	Soy/Mze/Soy/Mze + Rye	no CC	3	N _ _ _	N _ _ _
Howard		Soy	3	Soy + CC/Mze + CC/Soy + CC/Mze + rye	CC mixture (10)	3	N _ _ _	N _ _ _
Merrick	Entisols and Mollisols	Soy	0	Soy/Mze/Mze/Mze/Mze	no CC	0	N _ _ _ _	N _ _ _ _
Merrick		Soy	3	Soy + CC/Mze + CC/Mze + CC/Mze/Mze	interseeding CC (11)	0	N _ _ _ _	N _ _ _ _
Merrick		Soy	3	Soy + CC/Mze + CC/Mze + CC/Mze/Mze	postharvest CC (8)	0	N _ _ _ _	N _ _ _ _
Colfax	Mollisols	Soy	0	Soy/Mze/Soy/Mze/Soy	no CC	20	N _ _ _ _	N N Y N N
Colfax		Soy	3	Soy + CC/Mze + CC/Soy + CC/Mze/Soy	CC mixture (9)	20	N _ _ _ _	N N Y N N
Otoe	Mollisols	Triticale	8	Oats, Sorghum sudan, German millet + CC/Soy + triticale/ Mze + CC/ Soy + CC/ Mze + CC	singlespecies CC (1)	10	N _ _ _ _	N Y N N N
Otoe		Triticale	8	Oats, Sorghum sudan, German millet + CC/Soy + triticale/ Mze + CC/ Soy + CC/ Mze + CC	multispecies CC (6)	10	N _ _ _ _	N Y N N N
Nemaha	Mollisols and Entisols	Mze	4	Mze + CC/Wht + CC/Soy + CC/Mze + CC/Wht + CC	winter hardy CC (2)	30	Y Y N Y Y	N _ _ _ _
Nemaha		Mze	4	Mze + CC/Wht + CC/Soy + CC/Mze + CC/Wht + CC	winter terminated CC (2)	30	Y Y N Y Y	N _ _ _ _
Nemaha		Soy	4	Soy + CC/ Mze + CC/Wht + CC/Soy + CC/Mze + CC	winter hardy CC (2)	30	N Y Y N Y	N _ _ _ _
Nemaha		Soy	4	Soy + CC/ Mze + CC/Wht + CC/Soy + CC/Mze + CC	winter terminated CC (2)	30	N Y Y N Y	N _ _ _ _
Nemaha		Wht	4	Wht + CC/Soy + CC/Mze + CC/Wht + CC/Soy + CC	winter hardy CC (2)	30	Y N Y Y N	N N Y N N
Nemaha		Wht	4	Wht + CC/Soy + CC/Mze + CC/Wht + CC/Soy + CC	winter terminated CC (2)	30	Y N Y Y N	N N Y N N
Knox	Mollisols	Millet, oats, triticale	6	Warm season CC/Wht + CC/Field pea + CC/Mze + CC/	grazed CC mixture (12)	11	Y _ _ _ _	N _ _ _ _
Knox		millet, oats, triticale	6	Warm season CC/Wht + CC/Field pea + CC/Mze + CC/	ungrazed CC mixture (12)	11	N _ _ _ _	N _ _ _ _
Dodge	Alfisols and Mollisols	Soy	3	Soy + CC/Mze + CC/Soy + CC/Mze/Soy	intermittent CC (3)	6	N _ _ _ _	N _ _ _ _
Dodge		Soy	3	Soy + CC/Smal grain + CC/Soy + CC/Mze/Soy	continuous CC (3)	6	N _ _ _ _	N _ _ _ _
Dodge		Mze	3	Mze + CC/Soy + CC/Mze + CC/Soy/Mze	intermittent CC (1)	6	Y N Y N Y	N _ _ _ _
Dodge		Wht	3	Smal grain + CC/Soy + CC/Mze + CC/Soy/Mze	continuous CC (8)	6	Y N Y N Y	N _ _ _ _
Stanton	Mollisols	Mze	12	Mze + CC/Wht + CC/Soy + CC/Mze/ Soy + rye	CC rye (1)	20	N _ _ _ _	N _ _ _ _
Stanton		Mze	12	Mze + CC/Wht + CC/Soy + CC/Mze/ Soy + rye	CC mixture (4)	20	N _ _ _ _	N _ _ _ _
Seward	Entisols, Molisols and Alfisols	Soy	5	Soybeans/Oats Hay/Oats Hay/Oats Hay/Oats Hay	grazed CC (9)	5	Y _ _ _ _	N _ _ _ _
Seward		Soy	5	Soybeans/Oats Hay/Oats Hay/Oats Hay/Oats Hay	ungrazed CC (9)	5	N _ _ _ _	N _ _ _ _
Seward		cover crop	5	Soybeans/Oats Hay/Oats Hay/Oats Hay/Oats Hay	high diversity CC (6)	5	Y _ _ _ _	N _ _ _ _
Seward		cover crop	5	Soybeans/Oats Hay/Oats Hay/Oats Hay/Oats Hay	low diversity CC (3)	5	Y _ _ _ _	N _ _ _ _

[1] Crop abbreviations: Mze – maize, Wht – wheat, Soy – soybean, CC – cover crop

[2] Number in parenthesis indicates number of species in mixture

[3] Y=yes, N=no

Table S2. Details of area, number of contrasting management practice, replication, average plot size and individual soil composite sample of the ten fields included in this study.

County	Field area (ha)	Number of treatments (contrasting management practices)	Number of treatment replication	Average plot size (width x length)	Number of individual soil composite samples	Late-Fall sampling date
Greeley	32	2	6	74m x 412 m	16	October 22, 2019
Colfax	27	2	6	40 m x 623 m	12	November 5, 2019
Dodge	32	4	4	48 m x 392 m	16	November 6, 2019
Howard	39	3	7	52 m x 573 m	14	October 23, 2019
Knox	30	2	4	71 m x 72 m	8	November 8, 2019
Merrick	26	3	6	24 m x 670 m	18	October 29, 2019
Nemaha	8	6	4	9 m x 301 m	24	October 24, 2019
Otoe	41	2	4	161 m x 353 m	10	October 30, 2019
Seward	11	4	4	37 m x 127 m	16	October 24, 2019
Stanton	21	2	5	56 m x 376 m	14	November 15, 2019

Table S3. Descriptive statistics for the 21 measured variables collected in 2019 and included in the multivariate analysis with means and standard deviation (SE) for 0-5 cm soil depth across ten farm counties included in this study.

Soil health indicators	Soil management index[1]									
	CDI		CCU		YWSD		OAI		CL	
	0.1 - 0.44	0.45 - 1	0 - 0.49	0.5 - 1	0 - 0.5	0.5 - 1	0 - 0.1	0.1 - 0.2	0 - 0.5	0.5 - 1
NRCS[2]										
Infiltration (mm/hour^{-1})	149.6 (340.6)	217.0 (632.3)	82.3 (149.9)	499.0 (586.5)	143.0 (278.5)	230.0 (449.7)	197.7 (381.7)	73.1 (115.7)	204.2 (408.6)	120.1 (205.4)
Soil porosity (%)	53.90 (5.10)	54.98 (5.01)	53.50 (5.13)	56.97 (3.78)	54.31 (5.53)	54.22 (4.10)	53.95 (5.33)	55.51 (3.67)	55.9 (4.16)	51.75 (5.32)
Soil temperature (°C)	6.32 (2.80)	4.74 (2.54)	6.56 (2.58)	3.31 (2.39)	5.42 (2.55)	6.40 (3.15)	5.54 (2.94)	6.62 (2.11)	4.68 (2.34)	7.40 (2.68)
Volumetric water content (%)	25.85 (5.40)	26.45 (6.19)	25.39 (5.91)	28.23 (4.11)	24.38 (5.98)	29.06 (3.42)	25.76 (6.21)	27.06 (2.65)	25.89 (5.20)	26.28 (6.41)
Bulk density (g cm^{-3})	1.201 (0.135)	1.178 (0.138)	1.215 (0.139)	1.119 (0.098)	1.195 (0.150)	1.190 (0.106)	1.203 (0.144)	1.157 (0.095)	1.555 (0.121)	1.254 (0.139)
HSHT[3]										
Water Extr. Org. N (ppm)	12.32 (3.50)	11.43 (3.54)	11.32 (2.87)	14.08 (4.52)	12.42 (3.19)	11.27 (3.95)	12.16 (2.92)	11.37 (5.09)	12.51(3.50)	10.78 (3.33)
Water Extr. Org. C (ppm)	151.3 (40.2)	145.2 (39.1)	148.4 (36.8)	151.0 (48.2)	157.2 (41.1)	135.4 (33.60)	149.7 (36.2)	146.4 (50.6)	152.4 (40.6)	140.9 (37.0)
Water Extr. Total N (ppm)	22.02 (8.43)	20.33 (5.10)	19.23 (4.51)	28.58 (10.09)	21.41 (4.75)	21.32 (10.32)	22.01 (7.43)	19.07 (6.77)	23.57 (7.55)	16.67 (4.11)
Organic matter (% LOI)	3.68 (0.69)	3.56 (0.91)	3.47 (0.76)	4.15 (0.59)	3.61 (0.89)	3.67 (0.55)	3.54 (0.83)	3.95 (0.48)	3.59 (0.84)	3.73 (0.61)
24-h soil respiration (ppm CO$_2$)	49.29 (21.12)	50.42 (25.26)	44.49 (19.65)	67.79 (23.76)	80.76 (23.11)	47.92 (22.18)	47.11 (22.32)	58.37 (22.29)	51.33 (24.74)	46.16 (17.31)
Inorganic N (ppm)	10.80 (5.75)	11.71 (4.39)	10.0 (4.07)	14.70 (6.78)	11.15 (4.11)	11.13 (6.76)	11.75 (5.72)	9.08 (2.34)	12.73 (5.47)	7.49 (1.96)
Inorganic P (ppm)	16.04 (16.03)	16.18 (9.70)	13.41 (9.92)	25.89 (13.32)	14.99 (10.86)	17.96 (13.25)	14.35 (11.26)	21.93 (12.10)	19.33 (12.42)	8.87 (6.11)
Organic P (ppm)	3.93 (1.63)	4.67 (1.41)	4.17 (1.67)	4.36 (1.22)	4.54 (1.53)	3.62 (1.52)	4.14 (1.65)	4.46 (1.33)	4.79 (1.43)	2.87 (1.02)
Aluminum (ppm)	205.8 (37.2)	212.1 (52.1)	208.2 (42.3)	208.40 (47.8)	210.6 (44.0)	204.1 (42.5)	203.1 (42.2)	225.4 (43.6)	218.8 (41.1)	185.4 (39.7)
Calcium (ppm)	486.0 (90.4)	445.70 (86.23)	471.1 (91.1)	472.32 (90.29)	457.8 (94.3)	491.0 (81.2)	454.9 (90.1)	531.5 (63.2)	444.5 (89.9)	524.6 (66.0)
Sodium (ppm)	16.51 (3.62)	18.77 (3.02)	17.49 (2.97)	16.72 (4.79)	19.2 (3.1)	14.65 (3.0)	17.33 (3.40)	17.33 (3.59)	18.11 (3.72)	15.46 (1.54)
Manganese (ppm)	5.37 (3.40)	4.14 (1.58)	5.0 (3.0)	4.57 (2.55)	3.71 (1.77)	6.96 (3.31)	5.10 (2.90)	4.21 (2.79)	4.01 (1.97)	7.10 (3.59)
Magnesium (ppm)	104.9 (30.0)	107.2 (35.4)	97.1 (25.6)	135.7 (34.5)	112.3 (35.1)	95.14 (23.0)	102.8 (30.4)	115.8 (35.6)	109.4 (34.0)	97.4 (25.5)
Sulfur (ppm)	6.88 (7.70)	10.44 (9.79)	8.36 (9.78)	7.92 (4.11)	6.83 (3.85)	10.68 (13.12)	5.93 (3.73)	16.70 (14.60)	9.78 (9.68)	4.82 (4.51)
Potassium (ppm)	92.0 (42.7)	109.5 (47.2)	101.2 (48.42)	89.7 (30.4)	104.2 (51.8)	89.4 (29.6)	102.8 (47.9)	85.0 (29.1)	105.8 (46.7)	82.6 (37.2)
Soil health score	9.26 (2.66)	9.12 (2.96)	8.58 (2.63)	11.20 (3.08)	9.49 (2.88)	8.72 (2.55)	8.98 (2.57)	9.97 (3.27)	9.48 (3.05)	8.58 (1.91)
Number of observations	98	50	116	32	98	50	118	30	92	56

[1] CDI, CCU, YWSD, OAI, CL are the crop diversity index, years of cover crop use, years without soil disturbance, organic amendment index, and crop and livestock integration.

[2] Soil health indicators included in assessment protocol used by NRCS on conservation programs administered on privately managed lands.

[3] Soil health indicators included in the Haney soil health test (HSHT).

Table S4. Variance inflation factor analysis obtained from regression models shown in Table 2.

Soil health indicators	Intercept	Soil management index[1]				
		CDI	CCU	YWSD	OAI	CL
NRCS[2]		Variance inflation rate				
Infiltration (mm/hour^{-1})	0.000	1.364	1.526	2.256	1.383	1.567
Soil porosity (%)	0.000	1.310	1.488	2.172	1.406	1.595
Soil temperature (°C)	0.000	1.263	1.546	2.023	1.444	1.638
Volumetric water content (%)	0.000	1.340	1.665	2.483	1.481	1.895
Bulk density (g cm^{-3})	0.000	1.315	1.523	2.216	1.423	1.602
HSHT						
Water Extr. Org. N (ppm)	0.000	1.299	1.599	2.777	1.830	1.5177
Water Extr. Org. C (ppm)	0.000	1.337	1.417	2.393	1.405	1.640
Water Extr. Total N (ppm)	0.000	1.360	1.385	2.369	1.407	1.670
Organic matter (% LOI)	0.000	1.346	1.404	2.346	1.377	1.670
24-h soil respiration (ppm CO_2)	0.000	1.352	1.337	2.379	1.393	1.686
Inorganic N (ppm)	0.000	1.349	1.406	2.391	1.382	1.677
Inorganic P (ppm)	0.000	1.338	1.353	2.321	1.392	1.650
Organic P (ppm)	0.000	1.367	1.371	2.175	1.377	1.643
Potassium (ppm)	0.000	1.343	1.398	2.276	1.393	1.645
Calcium (ppm)	0.000	1.397	1.380	2.698	1.505	1.865
Aluminum (ppm)	0.000	1.375	1.425	2.222	1.365	1.707
Sodium (ppm)	0.000	1.255	1.533	2.588	1.507	1.678
Manganese (ppm)	0.000	1.339	1.414	2.302	1.386	1.602
Magnesium (ppm)	0.000	1.344	1.388	2.450	1.397	1.701
Sulfur (ppm)	0.000	1.224	1.404	2.420	1.307	1.705
Soil health score	0.000	1.339	1.355	2.368	1.400	1.676

[1] CDI, CCU, YWSD, OAI, CL are the crop diversity index, years of cover crop use, years without soil disturbance, organic amendment index, and crop and livestock integration.

[2] Soil health indicators included in assessment protocol used by NRCS on conservation programs administered on privately managed lands.

[3] Soil health indicators included in the Haney soil health test (HSHT).

Table S5. Condition index analysis obtained from regression models shown in Table 2.

Soil health indicators		Soil management index[1]				
	Intercept	CDI	CCU	YWSD	OAI	CL
NRCS[2]		Condition Index				
Infiltration (mm/hour^{-1})	1.0000	2.1723	2.4459	3.4967	5.2701	7.0569
Soil porosity (%)	1.0000	2.1863	2.5005	3.4577	5.3934	7.0702
Soil temperature (°C)	1.0000	2.1842	2.4948	3.3910	6.0470	7.0874
Volumetric water content (%)	1.0000	2.2003	2.4967	3.5100	5.4311	7.3537
Bulk density (g cm^{-3})	1.0000	2.1735	2.4837	3.4495	5.3798	7.0032
HSHT						
Water Extr. Org. N (ppm)	1.0000	2.1055	2.3860	3.3306	5.3929	7.1059
Water Extr. Org. C (ppm)	1.0000	2.1888	2.3943	3.3741	5.2791	7.2722
Water Extr. Total N (ppm)	1.0000	2.2005	2.4287	3.5010	5.2825	7.3520
Organic matter (% LOI)	1.0000	2.1964	2.4247	3.4158	5.2747	7.3189
24-h soil respiration (ppm CO$_2$)	1.0000	2.1986	2.4179	3.526	5.1837	7.2696
Inorganic N (ppm)	1.0000	2.1934	2.4049	3.4068	5.2769	7.3475
Inorganic P (ppm)	1.0000	2.2154	2.3997	3.6905	5.3100	7.3065
Organic P (ppm)	1.0000	2.1671	2.5002	3.6267	5.1598	7.1503
Potassium (ppm)	1.0000	2.1403	2.4334	3.3859	5.3219	7.2949
Calcium (ppm)	1.0000	2.2457	2.417	3.6593	5.4577	7.8128
Aluminum (ppm)	1.0000	2.0930	2.4585	3.3841	5.0280	6.9939
Sodium (ppm)	1.0000	2.1963	2.3332	3.2649	5.6064	7.3540
Manganese (ppm)	1.0000	2.1688	2.4072	3.3512	5.2002	7.2133
Magnesium (ppm)	1.0000	2.2055	2.3921	3.4309	5.2680	7.4086
Sulfur (ppm)	1.0000	2.2169	2.3421	3.4236	5.6548	7.2133
Soil health score	1.0000	2.1951	2.4282	3.4549	5.2839	7.2659

[1] CDI, CCU, YWSD, OAI, CL are the crop diversity index, years of cover crop use, years without soil disturbance, organic amendment index, and crop and livestock integration.

[2] Soil health indicators included in assessment protocol used by NRCS on conservation programs administered on privately managed lands.

[3] Soil health indicators included in the Haney soil health test (HSHT).

Table S6. Principal component analysis of 5 soil management indexes and 21 soil health indicators for 0-15 cm soil depth with eigenvalues and proportion of variability explained for the first two components (PC). Component correlation score are shown in percentage; highest loading in each component are bolded.

	PC1	PC2
Eigenvalue	5.36	3.68
Proportion	20.62	14.14
	Component correlation score	
Soil management index[1]		
CDI	**15%**	-3%
CCU	**38%**	**-28%**
YWSD	-11%	**-25%**
OAI	2%	-8%
CL	-10%	-11%
NRCS[2]		
Infiltration (mm/hour^{-1})	11%	-2%
Soil porosity (%)	11%	-3%
Soil temperature (°C)	-4%	-3%
Volumetric water content (%)	-2%	-10%
Bulk density (g cm^{-3})	**-23%**	6%
HSHT[3]		
Water Extr. Org. N (ppm)	**44%**	-4%
Water Extr. Org. C (ppm)	12%	-8%
Water Extr. Total N (ppm)	20%	6%
Organic matter (% LOI)	6%	-11%
24-h soil respiration (ppm CO_2)	5%	-4%
Inorganic N (ppm)	7%	6%
Inorganic P (ppm)	2%	0%
Organic P (ppm)	**31%**	29%
Potassium (ppm)	**36%**	**58%**
Calcium (ppm)	22%	-26%
Aluminum (ppm)	3%	5%
Sodium (ppm)	0%	0%
Manganese (ppm)	-8%	-2%
Magnesium (ppm)	6%	-6%
Sulfur (ppm)	1%	4%
Soil health score	**48%**	**-42%**

[1] CDI, CCU, YWSD, OAI, CL are the crop diversity index, years of cover crop use, years without soil disturbance, organic amendment index, and crop and livestock integration.

[2] Soil health indicators included in assessment protocol used by NRCS on conservation programs administered on privately managed lands.

[3] Soil health indicators included in the Haney soil health test (HSHT).

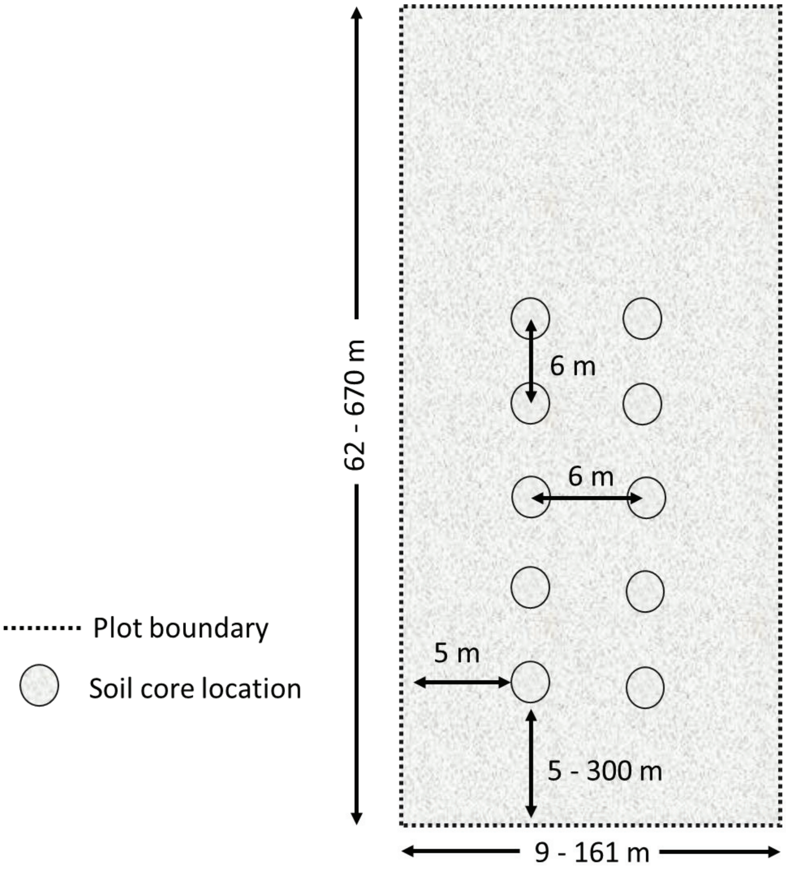


Figure S1. Layout showing the 6 m × 24 m area within each plot used for field measurements and soil sampling along with distance in between each measurement point and from the plot boundaries (not to scale).

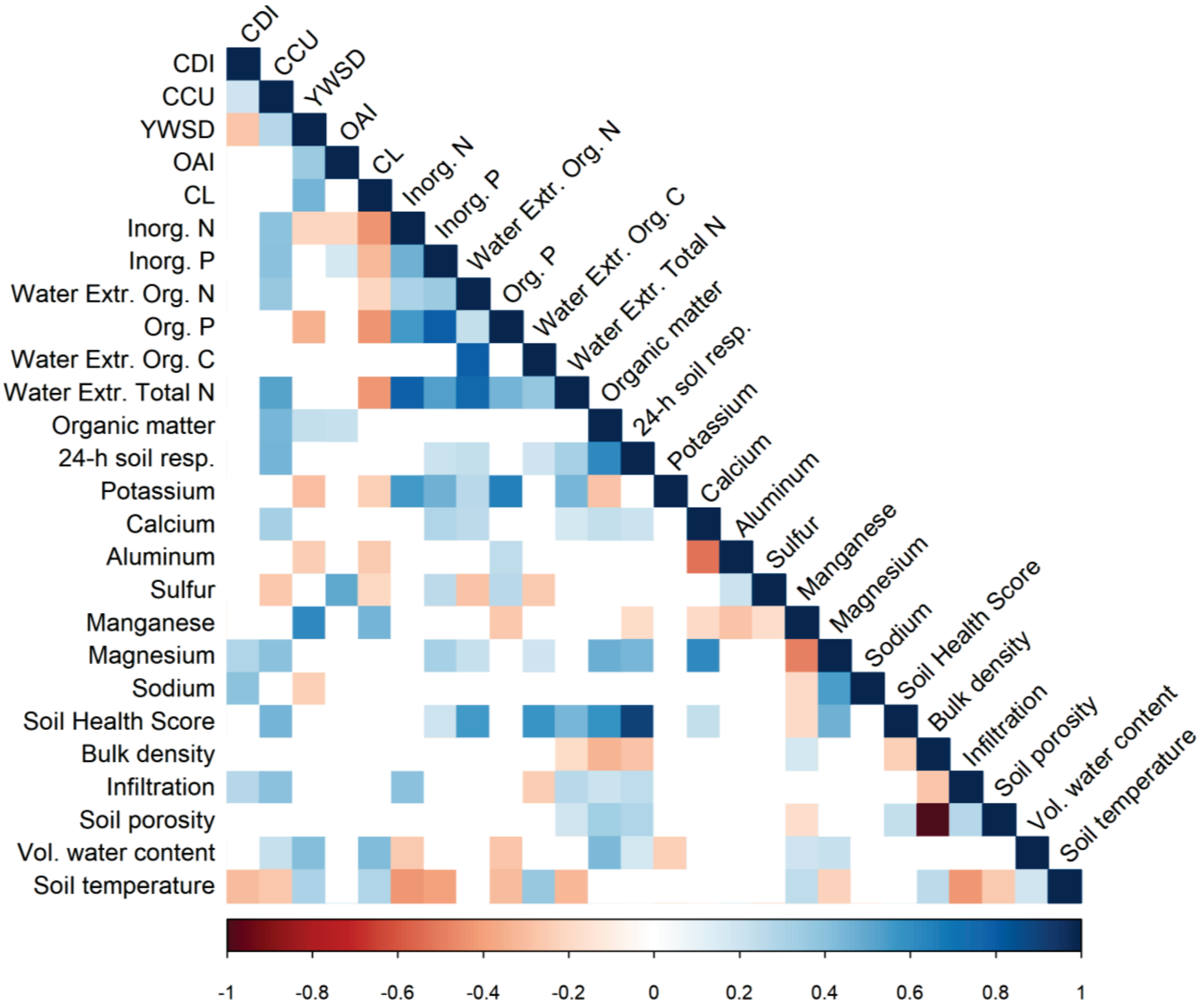


Figure S2. Pearson correlation analysis between soil properties used for PCA and multiple linear regression. Correlations with p-value > 0.05 are considered as insignificant and were left blank. CDI, CCU, YWSD, OAI, CL are the crop diversity index, years of cover crop use, years without soil disturbance, organic amendment index, and crop and livestock integration.

APPENDIX 2 SUPPEMENTARY MATERIAL CHAPTER 4

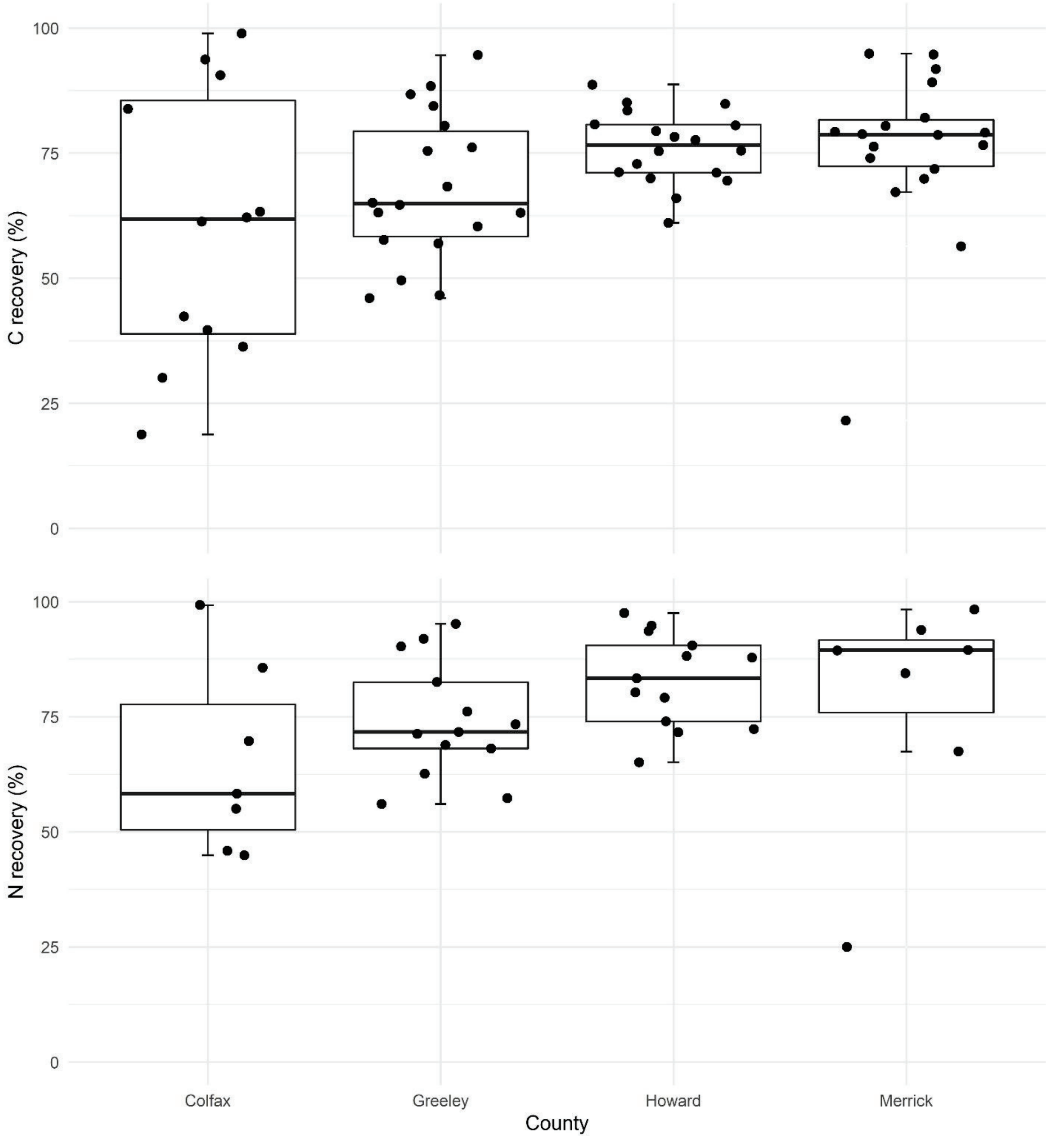


Figure S1. Organic C and total N recovery for the fractions analyzed in Colfax, Greeley, Howard and Merrick on-farm locations.

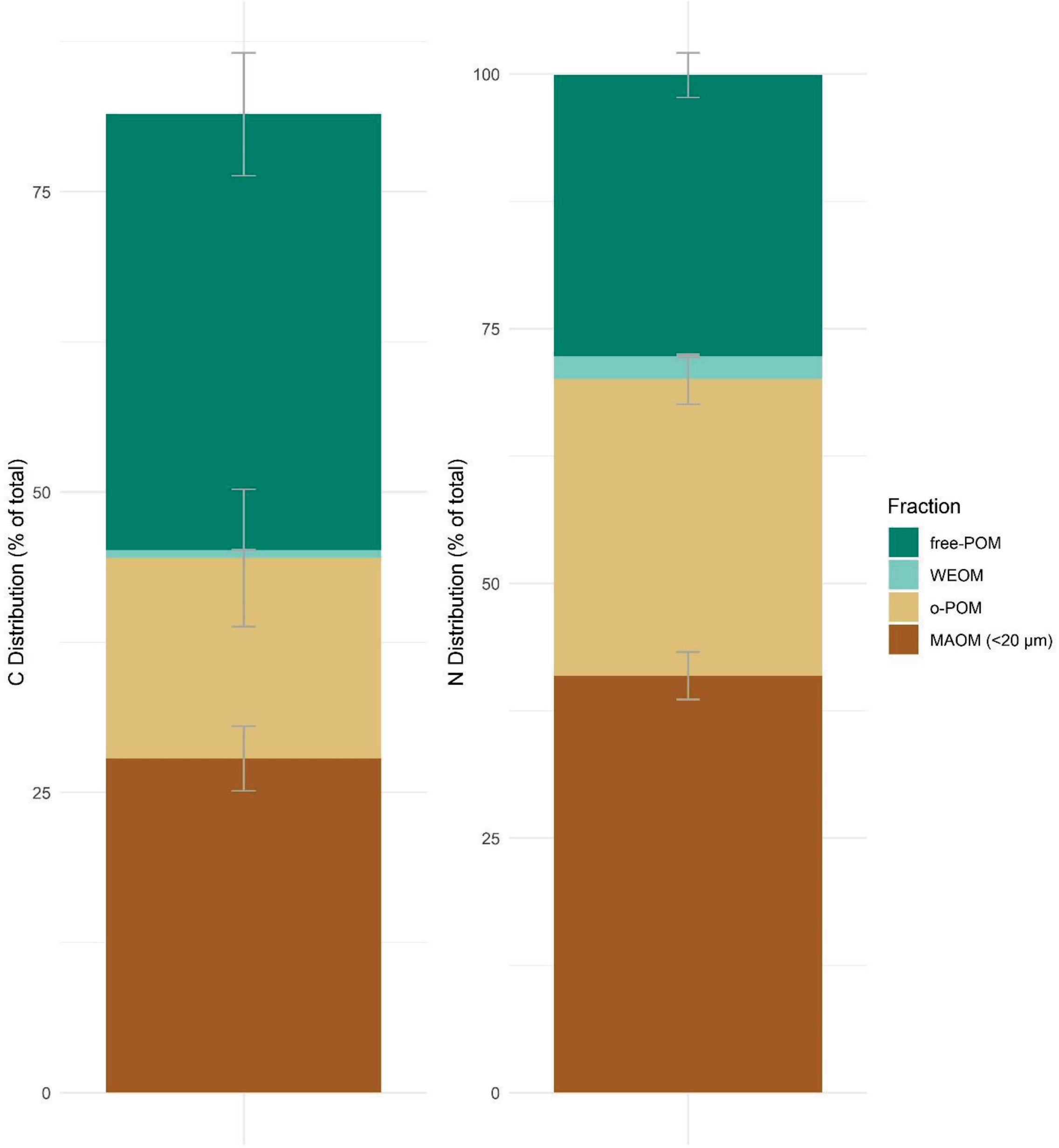
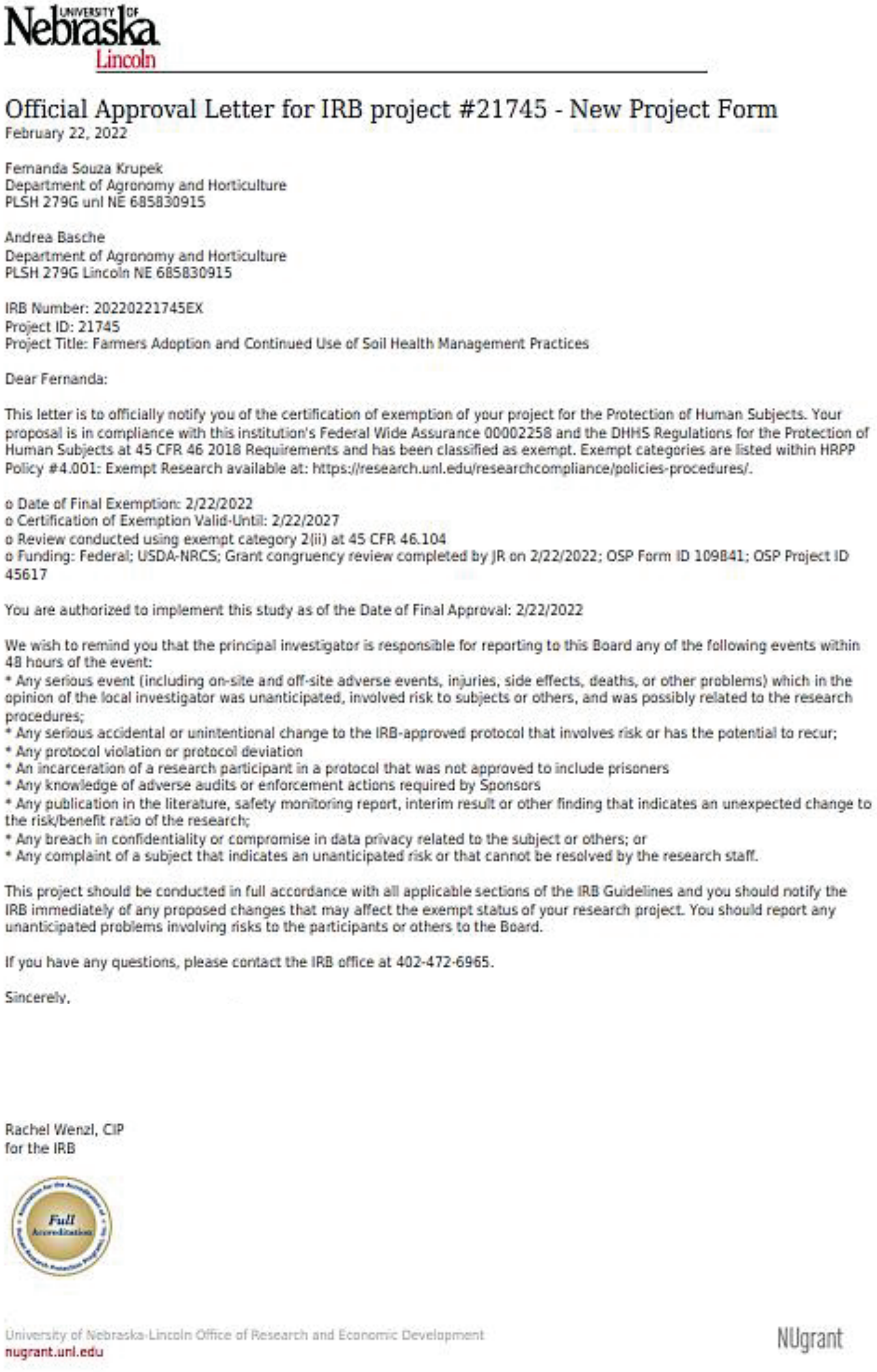


Figure S2. Carbon (left) and nitrogen (right) distribution (left) across SOM fractions. Error bars indicate standard error. Descriptors: free-POM= free particulate organic matter, WEOM = water extractable organic matter; o-POM = aggregate occluded POM; MAOM= mineral-associated organic matter.

APPENDIX 3 SUPPEMENTARY MATERIAL CHAPTER 5

IRB APPROVAL



University of Nebraska Lincoln

Official Approval Letter for IRB project #21745 - New Project Form

February 22, 2022

Fernanda Souza Krupek
Department of Agronomy and Horticulture
PLSH 279G unl NE 685830915

Andrea Basche
Department of Agronomy and Horticulture
PLSH 279G Lincoln NE 685830915

IRB Number: 20220221745EX
Project ID: 21745
Project Title: Farmers Adoption and Continued Use of Soil Health Management Practices

Dear Fernanda:

This letter is to officially notify you of the certification of exemption of your project for the Protection of Human Subjects. Your proposal is in compliance with this institution's Federal Wide Assurance 00002258 and the DHHS Regulations for the Protection of Human Subjects at 45 CFR 46 2018 Requirements and has been classified as exempt. Exempt categories are listed within HRPP Policy #4.001: Exempt Research available at: https://research.unl.edu/researchcompliance/policies-procedures/.

o Date of Final Exemption: 2/22/2022
o Certification of Exemption Valid-Until: 2/22/2027
o Review conducted using exempt category 2(ii) at 45 CFR 46.104
o Funding: Federal; USDA-NRCS; Grant congruency review completed by JR on 2/22/2022; OSP Form ID 109841; OSP Project ID 45617

You are authorized to implement this study as of the Date of Final Approval: 2/22/2022

We wish to remind you that the principal investigator is responsible for reporting to this Board any of the following events within 48 hours of the event:
* Any serious event (including on-site and off-site adverse events, injuries, side effects, deaths, or other problems) which in the opinion of the local investigator was unanticipated, involved risk to subjects or others, and was possibly related to the research procedures;
* Any serious accidental or unintentional change to the IRB-approved protocol that involves risk or has the potential to recur;
* Any protocol violation or protocol deviation
* An incarceration of a research participant in a protocol that was not approved to include prisoners
* Any knowledge of adverse audits or enforcement actions required by Sponsors
* Any publication in the literature, safety monitoring report, interim result or other finding that indicates an unexpected change to the risk/benefit ratio of the research;
* Any breach in confidentiality or compromise in data privacy related to the subject or others; or
* Any complaint of a subject that indicates an unanticipated risk or that cannot be resolved by the research staff.

This project should be conducted in full accordance with all applicable sections of the IRB Guidelines and you should notify the IRB immediately of any proposed changes that may affect the exempt status of your research project. You should report any unanticipated problems involving risks to the participants or others to the Board.

If you have any questions, please contact the IRB office at 402-472-6965.

Sincerely,

Rachel Wenzl, CIP
for the IRB

University of Nebraska-Lincoln Office of Research and Economic Development
nugrant.unl.edu

NUgrant

INTERVIEW MODERATOR'S GUIDE

Location: Zoom
Date: TBD
Process: Principal researcher is moderating every interview. Participants received the interview zoom link and will receive a follow-up reminder the day before the interview. If possible, participants are encouraged to connect to the meeting using a laptop or computer device (but cellphone is fine if participants prefer).

WELCOME & STUDY PURPOSE (5 minutes)

My name is Fernanda Krupek I am a doctoral student at the University of Nebraska-Lincoln and I will be moderating this interview.

You have been invited here today because we are interested in having a general discussion with you about your experience in adopting soil health-promoting practices and being part of the Soil Health Initiative and UNL On-Farm Research Network.

My role here is to ask questions and listen. The questions will center around your evaluation of soil health-related information, your affiliative networks, your experience with extension and agricultural conservation programs, and your reflections on long-term soil health practice adoption.

We welcome all opinions and will keep them confidential, so please feel free to say what you think. There are no correct/incorrect answers to any of the questions. Your feedback will be used to help public, private, and non-profit sectors evaluate their agricultural conservation programs.

This interview has been approved by Institutional Review Board (IRB) at the University of Nebraska-Lincoln. I am forwarding to your email a copy of the consent form which describes the goals of this interview and what we will be discussing today.

This session will be audio and video recorded to use as a reference when writing a report.

- Are there any questions before we begin?

DEFINITIONS & ICEBREAKER (5 minutes)

Let's start with two definitions as most of our questions will be centered on two terms: soil health and soil health-promoting (or soil health) practices. I am sharing a slide of the definitions.

Soil health (SH) is defined as the capacity of soil to function as a vital, living ecosystem that sustains plants, animals, and humans.

Soil health-promoting practices (e.g., SH practice) is often used to describe management practices such as the use of no or reduced tillage (where farmers avoid plowing soils), cover crop (plants grown to cover the soil after the main crop is harvested), diverse crop rotation (add small grains, cool-season, and pulse crops in the rotation over several years), and rotating crops with livestock grazing. This is a non-exhausting list, meaning other practices besides no-tillage, cover crop, crop rotation, and crop-livestock integration can also be considered soil health-promoting (for example, variable-rate N application, use of nitrification inhibitors, rotational grazing).

- To start our interview today, tell us a little about you, including your farm operation and experiences with the soil-health promoting practices you adopted/have tried or would like to try in your farm operation.

DISCUSSION SESSION (50 – 70 minutes)

For the next 50-70 minutes I will ask a series of questions and will also add the questions in the chat for you to see. If you need take breaks during the following hour or so, please let me know.

- What natural resource challenges or issues do you relate to when you think about soil health?
    - **Prompts**

- Water-related risks
- Climate change
- Groundwater quality

- This is a two-part question. The first question is, within the context of your farm operation, what are some of the consequences of soil degradation (loss of soil health)? And secondly, how do you see your role in solving this issue?

Next, we will discuss your experiences gathering and sharing information on soil health.

- When gathering information on soil-health promoting practices, who or what do you turn to for this information? In other words, what are your credible sources of information?

- Do you feel accessing needed information on soil-health promoting practices comes easily? What changes would you like to see? Do you use extension programs or resources?

- In general, do you talk to your friends and colleagues about soil health or soil degradation issues? Why?

- As a producer testing soil health-promoting practices, what would be important to encourage you to communicate about soil health practices and influence other farmers' adoption?
    - **Prompts**
        - Field days
        - Farmer's network

Next, we will discuss the groups of people you interact with when communicating soil health or soil-heath practices.

- When discussing soil-health promoting practices in the context of your farm operation, who have you talked about your experiences over the preceding 12-month period?
    - **Prompts**
        - Institutions
        - Crop advisors
        - Close friends and neighbor farmers

- This is a two-part question. The first question is within your network, what groups of people or individuals do you think have a positive influence on your decision to adopt soil health practice as part of your operation? And secondly, what groups of people would have neutral or negative influence?

- Do you feel your adoption of SH practices has influenced your neighbors to change their practices? Why?
    - **Prompts**
        - Proximity
        - Share similar ideas with neighbor producer

Now we are going to talk more about your evaluation of the costs and benefits of different soil health-promoting practices.

- What are the benefits [ask one practice at a time] "reduced tillage, cover crop, crop-livestock integration, and diversified crop rotation" would bring to your farm operation?

- What are the limitation or constraints [ask one practice at a time] "reduced tillage, cover crop, crop-livestock integration, and diversified crop rotation" would bring to your farm operation?

- In your farm operation, [ask one practice at a time] "reduced tillage, cover crop, crop-livestock integration, and diversified crop rotation" work well when combined with what other soil health-promoting practice? What would be the benefit of combining these practices?

Next, we will discuss your experiences in assessing soil health in your farm operation. Soil health in your farm can be measured using different commercially available tests.

- What soil testing for assessing soil health are you familiar with or already tried?

- This is a two-part question. The first question is, within the context of your farm operation, how do you see soil testing as a way to improve your understanding of, or care for, soil health? And secondly, what information do you look for in soil testing or soil health assessments in general?

Now we are going to talk more about your experiences as part of programs that encourage adoption of soil health practices.

- What has been your primarily/main personal motivation to enroll in conservation programs encouraging the adoption of SH practices?
    - **Prompts**
        - Financial aspects
        - Recognition from others
        - Guiltiness/regret if not helping the environment
        - Way to contribute to the environment
        - Sense of belonging

- After your period of agreement with NRCS ends (conservation program), do you plan to maintain these changes (adoption of soil health-promoting practices) without renewal of the contract? Why (what are your motivations to maintain or not the adoption of soil health practices, your long-term commitment to soil health practices)?

- How would being offered more program funds impact your level of effort to adopt SH practices in the long term (post your period of agreement with NRCS?

- Thinking about the state-wide programs and partnerships (like the SHI with UNL and NRCS) to enhance soil health practice adoption, what changes or improvements would you like to see in the program in order to adopt SH practices even after the period of the agreement ends (be fully committed to the change in land use or long-term soil health practice adoption)?
    - **Prompts**
        - Landowner's basic needs that could be integrated into program design and administration

Autonomy (freedom to express ideas and opinions)
Competence (ability to learn, accomplish a goal)
Relatedness (interact with other farmers)

- Assume that the Dean of Extension came into this room right now and ask for your advice about the best way to help farmers to adopt soil conservation practices in the long term. What would you tell them?

Our discussion is almost over, but we have one last section where we ask you to write down all thoughts related to the six short messages. Messages were shown in a ppt slide presentation using screen sharing.
Give 1-2 minutes to list each message. After they have listed the thoughts, have them talk through each of them and categorize as "positive", "negative, or "neutral." I would recommend you develop a color code and highlight the thought with corresponding color as they talk through it with you.
"In the fiscal year 2021, the Natural Resources Conservation Service (NRCS) made available **$22 million** for agricultural producers in **Nebraska** to adopt soil health-promoting practices through the Agricultural Conservation Easement Program (ACEP), Environmental Quality Incentives Program (EQIP), Conservation Stewardship Program (CSP) or the Healthy Forests Reserve Program (HFRP)."

"In the fiscal year 2021, the Natural Resources Conservation Service (NRCS) made available **$720 million** for agricultural producers **across the country** to adopt soil health-promoting practices through the Agricultural Conservation Easement Program (ACEP), Environmental Quality Incentives Program (EQIP), Conservation Stewardship Program (CSP) or the Healthy Forests Reserve Program (HFRP)."

"Soil health practices have been shown to bring significant **environmental benefits**. It is estimated that adoption of cover crops, reduced tillage, and diversified crop rotations on 100,000 acres over five years in Nebraska can store **150,000 metric tons of carbon**, prevent **375,000 tons of erosion** and deliver significant **water quality benefits**."

"Soil health practices have been shown to reduce the **negative environmental impacts** of agriculture. It is estimated that conventional agriculture over the last 160 years in Nebraska caused loss of roughly **7 inches of topsoil per acre** and several **impairments to water quality**."

"According to Census of Agriculture, cover crop acreage in Nebraska **doubled** from 2012 to 2017, but at a country level, only **4–5%** utilize cover crops. **Join your fellow American farmers** and ranchers in protecting our land by adopting soil health-promoting practices. Participate in conservation and join the other stewards to ensure healthier soil."

"According to Census of Agriculture, cover crop acreage in Nebraska **doubled** from 2012 to 2017, but at a country level, only **4–5%** utilize cover crops. **As an individual, you** can be part of changing these numbers by considering conservation efforts and soil health-promoting practices as part of your operation."

- Which of the messages can you identify (empathize) the most? Why do you think that is? (resonates better to you)

- Think about your neighbor farmer's practicing conventional agriculture, which of these messages would be most effective to convince them to adopt SH promoting practices? Why?
- If you could work on a message to be featured in a magazine or website to advocate for the adoption of soil health practices, what might that message say?

CONCLUDING DISCUSSION (10 minutes)

As was explained at the beginning of the session, the purpose of this interview was to gain an understanding of the process by which soil health practices are adopted and maintained in privately managed lands.

- Have you thought of anything else you would like to say that we have not discussed?

I am now going to try to summarize the main points from today's discussion (key messages and big ideas that developed from the discussion). The main topics were ….

- Is this an adequate summary?

Your comments today will be useful in developing policy tools and initiatives to promote soil health research and practices adoption in private land.

- Have we missed anything or are there any other comments at this time?

Thank you for taking time out of your day to share your opinions. Your participation is greatly appreciated and has provided valuable insight into this topic.

INTERACTIVE MAPPING EXERCISES

Decision-making interactive mapping exercise

In the envelope you will find several sheets of paper with the names of different people or groups who may or may not have an influence on your farm decision-making. For this activity, please note that there are two steps we are asking you to complete anonymously.

For Step 1: Please consider the people or groups that impact your **overall operation decision-making**. Place each of the people or groups on the circular grid (opposite side of this sheet of paper). The grid consists of concentric circles labelled with a scale from 1 to 5 moving outwards, with 'My decisions about my operation' at the center. People or groups viewed as having a larger impact on farm decisions should be placed closer to the center of the grid and those having lesser impact should be placed towards the outer edge of the grid. You may also choose not to place some of the people or groups on your circle if you feel they do not have an impact on your decision-making.
Once you have placed all of the people or groups on your circle, write down the number where each person or group was placed on your circular grid (only using the numbers 1 through 5) on the back of each small sheet of paper on the side labelled **overall**.

For Step 2: Please consider the people or groups that impact your **operation decision-making related to soil health management.** Again, place each of the people or groups on the circular grid (opposite side of this sheet of paper). The grid consists of concentric circles labelled with a scale from 1 to 5 moving outwards, with 'My decisions about my operation' at the center. People or groups viewed as having a larger impact on farm decisions related to soil health should be placed closer to the center of the grid and those having lesser impact should be placed towards the outer edge of the grid. You may also choose not to place some of the people or groups on your circle if you feel they do not have an impact on your decision-making related to soil health.
Once you have placed all of the people or groups on your circle, write down the number where each person or group was placed on your circular grid (only using the numbers 1 through 5) on the back of each small sheet of paper on the side labelled **soil health.**

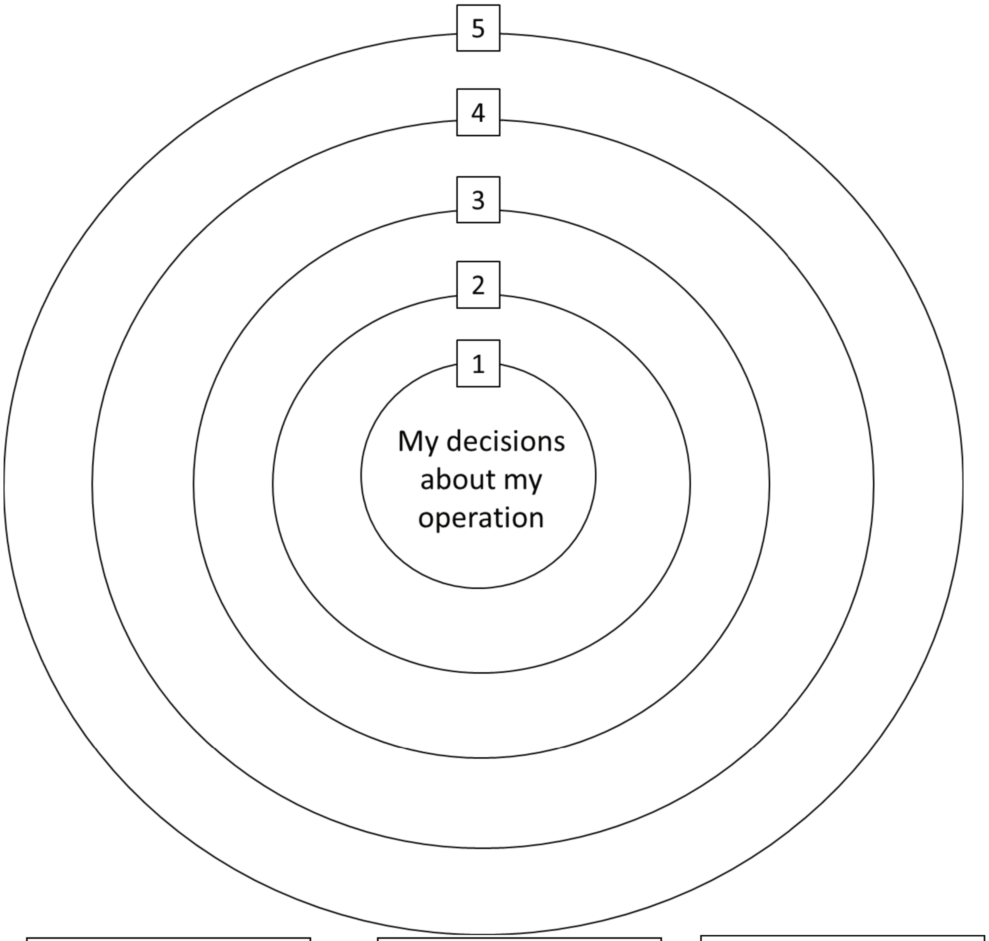
If you would like to share with us any feedback about your answers, you can respond to the following:

- What are the qualities of the people or groups whom you ranked higher or lower from an overall operation decision-making standpoint?

- What are the qualities of the people or groups whom you ranked higher or lower from a soil health related decision-making standpoint?

Invitation to participate in a follow-up interview: We are conducting interviews as part of a research study to increase our understanding of the human dimensions of soil health-related practice adoption. Would you be willing to participate in a follow-up interview after this meeting?

____Yes Name:
____No Preferred contact information (phone or email):



My Natural Resource District

Commodity groups

Ag banker/lender

My fertilizer applicator or retailer

Insurance agent

Other farmers on my community

A family member or farm partner

USDA NRCS

Farm Bureau

My county Extension agent

University extension "broadly"

My crop advisor/ consultant

Conservation practice interactive mapping exercise

In the envelope you will find several sheets of paper with the names of different conservation practices. For this activity, please note that there are two steps we are asking you to complete anonymously.

For Step 1: Please consider the different practices and **how large of impact you believe that they have on soil health.** Place each of the practices on the circular grid (opposite side of this sheet of paper). The grid consists of concentric circles labelled with a scale from 1 to 5 moving outwards, with 'conservation practices' at the center. Practices viewed as having a larger impact on soil health should be placed closer to the center of the grid and those having lesser impact should be placed towards the outer edge of the grid. You may also choose not to place some of the practices on your circle if you feel they do not have an impact on soil health.
Once you have placed all of the practices on your circle, write down the number where each practice was placed on your circular grid (only using the numbers 1 through 5) on the back of each small sheet of paper on the side labelled **impact.**

For Step 2: Please consider the different practices and **how likely you are to recommend a conservation practice to a farmer**. Place each of the practices on the circular grid (opposite side of this sheet of paper). The grid consists of concentric circles labelled with a scale from 1 to 5 moving outwards, with 'conservation practices' at the center. Practices that you are more likely to recommend should be placed closer to the center of the grid and those that you are less likely to recommend should be placed towards the outer edge of the grid. You may also choose not to place some of the practices on your circle if you feel you would recommend them to a producer.
Once you have placed all of the practices on your circle, write down the number where each practice was placed on your circular grid (only using the numbers 1 through 5) on the back of each small sheet of paper on the side labelled **recommend.**

If you would like to share with us any feedback about your answers, you can respond to the following:

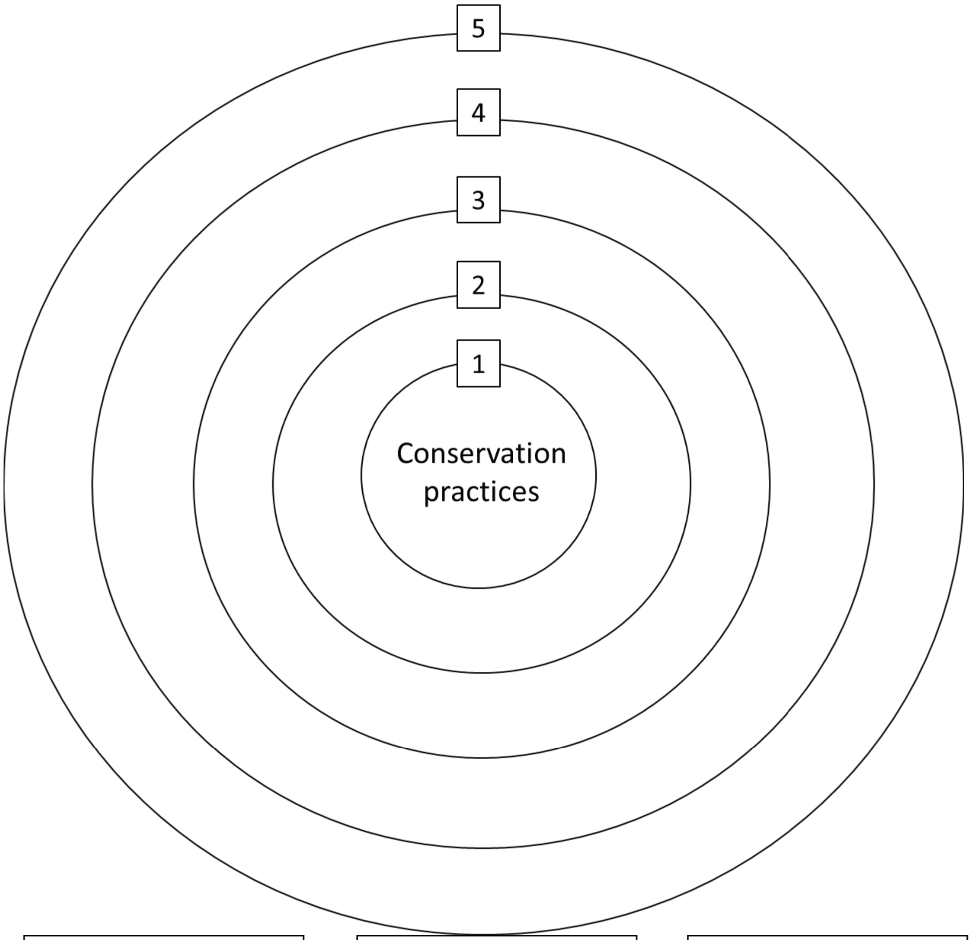
- Why did you rank different conservation practices as having a greater or lesser impact on soil health? Why are you more or less likely to recommend different conservation practices to producers?

- How do you feel soil conservation is a part of your role?

Invitation to participate in a follow-up interview: We are conducting interviews as part of a research study to increase our understanding of the human dimensions of soil health-related practice adoption. Would you be willing to participate in a follow-up interview after this meeting?

____Yes Name:

____No Preferred contact information (phone or email):



Reduced-till

Forage/biomass establishment

Riparian buffers/filter strips

Cover crops

Regular soil testing

Integrated Pest Management

Compost application

Mulching

Rotational or prescribed grazing

Alternate Crop Rotation

No-till

Variable rate nutrient management

RESEARCHER POSITIONING AND REFLEXVITY

I have included here a summary of my past experiences, biases, and motivations to work on this research about landowners' adoption and behavioral persistence related to soil health practices. This will help the reader to understand some intrinsic subjectivity that could influence the interpretation of the results (Merriam, 1988).

I am originally from Brazil and was raised in Sao Paulo State, the financial center and one of the most populous cities in the Southeast Region of Brazil. I received my bachelor's degree in Agronomy from the University of Sao Paulo. My interest in agricultural sciences started as crop production because I grew up in my uncle’s corn, soybean, and coffee farming operations. The opportunity of attending college, as the second in my family to pursue high education, represented a breakthrough in my career and role as a woman in agriculture. I wanted to take my education further and began to see academia as a way to promote equitable, healthy, profitable, and resilient food systems.

I had the opportunity to join the Horticultural Sciences Department at the University of Florida, first as an intern and later as a master student, working on potato postharvest quality and produce shelf-life; this was my first experience with U.S. agriculture. Even though it was not planned for my main funded project, I was interested in incorporating social science research with a focus on consumer behavior. More specifically, to understand public perception related to potato external appearance and how consumers form attitudes towards “ugly” produce, in particular, potato produce that is deformed, wonky, crooked, or misshapen. Due to time constraints, I could not proceed with this social-sciences related project. However, the experience of presenting in field days, interacting with farmers, and understanding that agricultural extension (researcher-farmer collaborations) is not well established in Brazil gave me a new appreciation for the work farmers do. Also, I gained a better understanding of how social science research and extension efforts can ensure that researchers are focusing on the relevant topic and that farmers are benefiting from the knowledge gained in the research.

After graduation, I took the opportunity to start my Doctoral degree in Agronomy and Crop Production at the University of Nebraska-Lincoln, where I am part of a statewide project involving 17 on-farm locations, dozens of extension agents as well as partners across the state with the USDA Natural Resources Conservation Service. The overarching goal of this work is to better understand the biological and ecological processes that govern soil health-related management practices. Even though I am pursuing research projects predominantly in crop and soil science, I have a career interest in extension-related work that includes social science research to better understand the human dimensions of soil health-related practice adoption.

The more I interact with farmers, the more of a need I see for effective farmer’s behavioral persistence in agricultural conservation practices. Based on conversations I have had with extension educators, farmers, and NRCS soil scientists and field staff, I have anecdotal evidence that farmers’ social network and sources of information is key in farmer’s decision and long-term success of conservation incentives and on-farm research programs.

My Ph.D. advisor is Andrea Basche whose research interests also encompass the human and policy dimensions of agricultural decision-making. Under her supervision, I contributed to a publication detailing how we have integrated farm simulation platforms into an undergraduate crop management course to understand students’ skills and confidence gain in decision-support technologies. This was my first study applying a qualitative approach, grounded theory, and coding interview questions. Over the last 4 years, I took three main classes that have helped me to propose the current research. The classes included Communication theories and strategies for agriculture and natural resources, Research methods in leadership education, and Qualitative approaches to educational research. Thus, my prior knowledge, gained through coursework and research related to science communication and qualitative research methods can influence me as a researcher (Charmaz, 2014). However, my goal is to remain as objective in my analysis and reporting as possible, but I recognize that complete objectivity is impossible.

The four-level framework for conducting research study proposed by Crotty (1998) consisted of epistemology, theoretical perspective, methodology, and methods of data collection. The epistemology (researcher's view of how knowledge is constructed) influences both theoretical perspective and methodology. As an agronomist, I study crops and soils deductively and empirically. However, the objectivity and deductive reasoning used to study the biological and ecological processes that govern soil health-related management practices cannot be used to understand the human dimensions of conservation practice adoption and continued use. Constructivism will be the epistemology used in this social science study. As I constructivist researcher, I believe that reality or interpretation of a single event is constructed out of interactions between humans (researcher-participants) and their worlds (Merriam & Tisdell, 2016). Essentially, there is no single, observable reality but multiple subjective realities constructed from what individuals are given to work within their own reality (Crotty, 1998). Informed by constructivism, the theoretical perspective for this research will be pragmatism.

As a student working with participatory on-farm research, I have learned the importance of acknowledging the limitations of working with on-farm trials (in particular for hypothesis testing related to crop and soil responses) and adjusting the expectations accordingly. Thus, flexibility is a key component in on-farm research and for this reason, I see my choices of research approaches as pragmatic. Pragmatism is concerned with solving a research problem more so than following a specific, scientific method (Charmaz, 2014). As a graduate student working on applied agricultural research, I am concerned with the practical implications of my research, the outcomes, and the consequences of what is studied. Thus, I believe multiple perspectives, along with facts and values, are necessary to address emerging problems when using a pragmatist approach (Charmaz, 2014).