THESIS

WHO WILL ANSWER THEIR QUESTIONS? A MIXED-METHODS STUDY ON SUPPORTING THE RESEARCH NEEDS OF PRODUCERS INNOVATING IN SOIL HEALTH

Submitted by

Lauren M. Hafford

Department of Soil and Crop Sciences

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2026

Master's Committee:

Advisor: Meagan Schipanski

Josh Sbicca
Tori Anderson Noell

ABSTRACT

WHO WILL ANSWER THEIR QUESTIONS? A MIXED-METHODS STUDY ON SUPPORTING THE RESEARCH NEEDS OF PRODUCERS INNOVATING IN SOIL HEALTH

Producers who are innovating in soil health generate complex and multidisciplinary questions about their ecosystems at a rate that far outpaces the ability of academia to address. Exploring these questions represents one piece of the intellectual labor needed to implement soil health practices successfully on a working farm or ranch, and many producers engage in independent on-farm research projects to provide this insight. Such producer-led research represents a large and untapped resource which could supplement academia's current on-farm research programs. Furthermore, there is a lack of responsive and cost-effective soil health metrics to quantitatively evaluate the soil health outcomes of single-season management changes. My mixed-methods research included qualitative interviews and thematic analysis with producers and academic researchers alongside the evaluation of two soil health indicators. First, to explore collaboration opportunities for on-farm experimentation I conducted semi-structured interviews with 10 academics and 7 producers. The results showed that (1) regenerative agricultural operations are more complex to manage than their conventional counterparts, (2) neither academia nor soil health testing were mentioned as a resource by the producers to address this complexity, and (3) all the researchers (academia and producers alike) were interested in doing more highly collaborative on-farm research, despite the additional challenges inherent in on-farm research. Second, to find a soil health indicator that producers could use to help them quantify single-season changes in soil health, I evaluated aggregate stability using the SLAKES smartphone app and the tea bag index for their sensitivity to changes in management in experiment station and producer field soils with paired treatment/control strips. I developed new protocols for the tea bag index that only require equipment readily available to producers, then incubated green tea in the field for 30 days and in a laboratory incubator for 5-90 days, to determine if green tea decomposition varied between treatment and control soils. I measured aggregate stability of the same paired soils with the SLAKES app, and correlated the SLAKES and green tea data with commercial lab soil health and microbial community test results. Across this study, the decomposition of green tea was only able to differentiate between treatment and control soils for 18% of the measurement points. Focusing only on the long-term experiment soils with known differences in soil health, green tea was able to differentiate treatment contrasts for 22% of the measurement points. I evaluated varying the decomposition duration and found that there was no one time point which consistently detected differences between treatment contrasts across sites. The SLAKES app could not differentiate between any of the treatment contrasts. I found no correlations between green tea decomposition and other laboratory measures of soil health except for a strong negative correlation with aggregate stability from the SLAKES app. I cannot recommend that producers invest their time to perform either one in treatment/control trials on their farms.

ACKNOWLEDGEMENTS

This thesis was written in cooperation with several farmer collaborators from CO, KS, and the Jemez Pueblo. While the Jemez Pueblo farmers are farming on some of their ancestral homelands, the other cooperators are farming on the ancestral homelands of the Arapahoe, Pawnee, and Kaw Nations.

—

I have so many thank-you's to give!

Troy for finding joy everywhere. Literally everywhere.

Halla and Signy for making me laugh all the time, and for some clutch assistance at that one 4H event, and doing data entry. Thank you for being weird with me.

Mom and Dad for all the things!

JONI!!!! You are a star.

Curt, Pat, Morgan and Kerry Sue, for being my mentors from the very beginning of my journey. Thanks for emergency-inviting basically the whole CCTA board to that first soil health roundtable - so much came from that day! Everyone in the WSARE project for everything you contributed to the project and to this thesis, and for your friendship! Roger and Bryn, Clifford, Justin, Jennifer, Steve, Esther, Francessca. All the producers from FARMS, for teaching me most of what I know about soil health, especially Kevin, Stu, Storm, John, Jeff, and Jolene.

Dr Holmes, you are a powerhouse!

Everyone in the Agroecology Lab, and especially thanks to Andrea for so much help through this journey. And to Tigist for getting absolutely covered in ticks with me in Kansas. I'll never forget that trip.

Josh for radicalizing me against capitalism.

Meagan! You are the literal best advisor. You rock.

—

This work supported by Western SARE project #SW23-952

DEDICATION

To Pronk, Fish, and Citrus aka Sir John Orange Peel.

I know you would happily sit on this if I printed it out.

TABLE OF CONTENTS

Chapter 1

Introduction

Agricultural land is increasingly being asked to provide ecosystem services beyond food production that were previously services only expected from unmanaged lands (Ellis et al., 2019), including carbon sequestration, pollinator support, and water purification. These ecosystem services can be provided by agroecosystems when adopting systems of soil health which implement the five soil health principles: minimizing soil disturbance, increasing cover, increasing diversity, increasing living roots, and optionally integrating livestock (Natural Resources Conservation Service, n.d.). These principles are rooted in Indigenous knowledge, though this is rarely acknowledged in modern discourse (Peña et al., 2017; Sands et al., 2023). There has been abundant research into individual soil health practices in the semi-arid region of the High Plains, and alongside this, the adoption rate of individual soil health practices is growing (Noble Strohm et al., 2025; Núñez et al., 2022; Rosenzweig, Fonte, and Schipanski, 2018; Rosenzweig, Stromberger, and Schipanski, 2018). On-farm research after long-term implementation is increasingly showing that the stacking of multiple practices provides greater ecosystem benefits than single practices in isolation (Prairie et al., 2023). Despite the benefits such stacking provides, research into transdisciplinary agroecological systems integrating multiple soil health practices continues to be under-represented in the literature, and concomitantly, adoption rates of systems of soil health in this region are equivalently rare and on the margins.

The barriers to adopting soil health practices has been well-studied. Notably, studies are often framed around single practices in isolation (Baumgart-Getz et al., 2012; Carlisle, 2016; Fleckenstein et al., 2020; Frankel-Goldwater et al., 2024; Hansen et al., 2012; Lemke et al., 2024; Roesch-McNally et al., 2018; Victoria et al., 2025). Producers face a whole host of unknowns when trying to implement new practices; see Carlisle (2016) for an excellent review. The challenges in their review spanned five dimensions: (1) Agronomic challenges included new practices detracting from cash crops, including timing, interference with harvest, and moisture depletion, as well as the complexity that new practices often add to an agricultural operation. (2) Financial challenges were dominated by the opportunity cost of a practice, such as if the practice displaced a cash crop. Other financial challenges included a lack of access to specialty equipment, especially to temporarily try out a new practice. It was also mentioned that there was a scale-dependent ability to defray risk and cost associated with new practices; smaller operations might be more adept at noticing issues arising from poor soil health management, but larger operations were more financially equipped to implement. (3) Policy challenges were centered around restrictions to crop insurance when adopting soil health practices, and various disqualifications from government programs. (4) Knowledge barriers included not knowing how to successfully implement the practices in their context or optimize them in subsequent years, alongside not knowing how to measure the impacts of soil health practices under evaluation. (5) Social barriers included aesthetics, community definitions of a good farmer and good stewardship, and doing right by your neighbors (Carlisle, 2016). While this is not a comprehensive list, together these items (and their interactions) show the complexity faced by producers when implementing soil health practices.

Related to the financial barriers listed above, land tenure can also be a major factor in implementing soil health practices. Having land to manage in the first place, whether that's leased or owned, is a fundamental prerequisite to practicing soil health. In that light, it is critical to take into account the fraught history of land ownership in the US, especially the dispossession of land from Indigenous and Black ownership. The work in this thesis was done with partners in the Jemez Pueblo and Kansas Black Farmers Association, and land tenure followed different trajectories for these two groups. The Jemez people are currently farming, hunting, gathering, and living in the Jemez Mountains and the valley below, on a portion of their ancestral lands. Indeed, one participant said, "we are all 1,000-year-old farmers," as the Pueblo have been farming these lands long before colonization (R. Fragua, personal communication, November 2023). Historically, hunting and grazing lands were understood to be separated by geographical boundaries between Pueblos, and the lands within each Pueblo were held in common (J. Casiquito, personal communication, June 2026; Rothschild, 2008). When the Spanish colonizers arrived, they extracted labor and coerced religious conversions from the Pueblos using exemplary violence (Dunbar-Ortiz, 1980). An alliance among the majority of the Pueblos in the area enabled the Pueblo Revolt of 1680, which successfully drove the Spanish out of the region entirely. When the Spanish eventually returned, it was with greater respect for the religious and economic rights of the Pueblos, and ancient Pueblo land use patterns profoundly influenced how the colonizers structured policy (Dunbar-Ortiz, 1980; Rothschild, 2008). However, while the law supported Indigenous land rights, these were frequently violated and encroachment was common (Jenkins, 1972). A brief period of Mexican Independence granted the Pueblos citizenship and title to all their lands. When US colonizers arrived after the Mexican-American war in the late 19th century, the US government enacted large-scale dispossession of Pueblo lands by arbitrarily deeming what systems of land 'ownership' were allowed. The Anglo-American surveying system subdivided land into square sections, a pattern that accommodated the market economy but was incompatible with the elongated and patchwork shapes that the arable land took in the Jemez valley. Additionally, while lands held in common were a critical foundation for life in the valley, the US invalidated this form of ownership. Plots that were not allotted to individual owners were deemed to be US public domain and sold off to homesteaders, including . For plots allotted to individuals, the US government introduced costly bureaucratic barriers to clearing the titles of the old Spanish land grants

(Dunbar-Ortiz, 1980; Ragsdale, 2021). Despite these powerful processes of dispossession, the people of the Jemez Pueblo successfully fought to retain ownership of a portion their ancestral lands, and these rights are federally recognized today. While they never ceded title to Redondo Peak and the Valles Caldera, two sites of major religious and ancestral importance, they have federally-recognized access rights and are continuing the fight with numerous lawsuits in the last decade to restore ownership (Ragsdale, 2021).

For the Black farmers in Kansas, the land tenure journey starts in 1865 after Emancipation, when General William Sherman promised every freedman “forty acres and a mule." Even though that promise was swiftly reneged, Black landownership rose to a peak of 16-19 million acres, or 14 percent of farmland, by 1920. This was despite ongoing brutal racism: maiming, lynching, burning, economic violence, and legal violence, in addition to banks refusing to lend money and white landowners refusing to sell to Black people (Edwards and Friefeld, 2023; Francis et al., 2022; Penniman, 2018). The Civil Rights Act of 1964 launched an era that promised free treatment and prosperity for all. While there were some major wins in civil rights, this time period also saw a staggering 88% decline in Black farmers in ten southern states, alongside a smaller decline in white farmers (58%). Policies at the USDA supported large-scale, capital-intensive, wealthy, white, scientific farmers, at the expense of smaller-scale, traditional, and/or Black-owned farms. It erected barriers for minority and female farmers to obtain allotments (Schneider, n.d.), loans, or information (Daniel, 2013). Today, 1% of farmers are Black, and they own 2 million acres or 0.5% of US farmland. This loss represents $326 billion worth of acreage (Francis et al., 2022; Jordan, 2021; Penniman, 2018). Today, the average income of a Black farming household is $19,600, compared to $52,300 for white farming households (Schneider, n.d.). To address these inequities and open the doors for Black farmers to own land and engage in soil health practices, it is necessary to dismantle the systems that created them. The USDA needs to end the racist practices that have prioritized white farmers, heirs property laws need to be reformed to prevent forced sales of land held in common, and funding needs to increase to Black farmers and Black farming organizations, to rebuild the land base that was lost or stolen over the past century. There is hope, borne from organizations who fight tirelessly to restore justice, including one notable example: the Kansas Black Farmers Association (KBFA), founded in 1999. The grants that KBFA are pursuing, the coalitions they are forming, and the vision that they are pursuing, is changing the landscape for Black farmers in Kansas. Graham County, where KBFA is headquartered, is the only county in Kansas to see an increase in Black land ownership in recent years. They have evaluated what needs to be done to restore farmground to Black ownership, they are navigating a challenging funding landscape, and they are enacting these steps, creating the world they want to live in today, cooperatively and collectively.

If these barriers to adopting soil health are well-known and well-studied, why aren't land grant university researchers making more progress on addressing them? In many ways the current system of agricultural research is not well-adapted to support producers innovating in soil health. Current research regimes at land-grant universities, including investment in research programs and equipment, are shaped by the accumulation of previous work which have been structured to serve dominant cash crop systems (Carolan, 2005; Vanloqueren and Baret, 2009). Additionally, the current extension-mediated knowledge delivery pipeline situates the producer at the end of the process as receivers of knowledge, instead of active participants shaping the research from the beginning (Röling, 1985; Waithaka, 2005), which hinders producers' own research questions being included on the research agenda. Additionally, within the dominant framework of agro-innovation at land-grant universities, there are social norms which constrain the research questions being asked and the acceptable methodologies being employed to research them (Friedrichsen et al., 2021). The dominate paradigm privileges technological and commercializable solutions (e.g., genetic engineering) over integrated, ecological, systems-based solutions. As explained in Vanloqueren and Baret (2009), "science policies are explicitly and increasingly oriented towards growth and national competitiveness," and this is revealed in funding structures, where increasing reliance on public-private partnerships and industry capture of research programs have redirected towards innovations ripe for commercialization. In contrast, the ecosystem services provided by agroecological innovations are considered true public goods because these services typically cannot be captured by markets (Vanloqueren and Baret, 2009), a notable exception being carbon credit markets. Importantly, changing funding landscapes have shifted definitions of a 'public good' to include a 'commercializable good', de facto a private good (Ellis et al., 2019). Compared to genetic engineering, agroecology research requires more work and time to achieve similar career-advancing outputs because it requires broader interdisciplinary work, moves more slowly, and results in fewer publications (Vanloqueren and Baret, 2009). To make better progress on addressing barriers to adopting the soil health principles, it is likely that a disruption is needed in the current land-grant paradigm which marginalizes agroecological research and situates the producer at the end of the knowledge generation process.

Agroceology researchers in academia can help enable large-scale provisioning of ecosystem services by actively and intentionally supporting producers innovating in soil health. Land grant research exists only as a peer-reviewed paper until it is put into practice by producers, and centering them in the entire process can lead to better outcomes (Jackson-Smith et al., 2018). Producers can be invited to help define research agendas and research questions, specify trials, be involved in the research itself, and help interpret results so that the research can support their intrinsic motivations to implement soil health (Bagnall et al., 2020; Deci and Flaste, 1995; Friedrichsen et al., 2021; Jackson-Smith et al., 2018). Caution is needed to avoid over-burdening their time: producers don't get paid to do this research, academics do (Nielsen, 2008). First-hand experience with soil health practices was found to be an excellent vehicle to address some of the knowledge gaps inherent in implementing soil health (Carlisle, 2016), and producers experimenting first-hand with soil health practices represent a substantial intellectual resource. Academics can invite them into the process as co-researchers, supporting their on-farm research programs with the resources available to academia. Some emerging models of highly collaborative on-farm research aim to achieve this, including the On-Farm Experimentation model proposed in Lacoste et al. (2021), the Practical Farmers of Iowa, and some on-farm research networks (Asprooth et al., 2023; Carlisle, 2016; Jackson-Smith et al., 2018; Lacoste et al., 2021). Importantly, some are calling for producers and especially Indigenous land stewards to be explicitly recognized as researchers and scientists in this model (Peña et al., 2017).

When experimenting with soil health practices, researchers (producers and academics alike) use indicators of soil health to gauge the efficacy of how the practice was implemented within the context. Currently, there is much active research into developing soil health indicators that are sensitive enough for this purpose and are meaningful to producers (Bagnall et al., 2023; Doran and Zeiss, 2000; Keuskamp et al., 2013). Measuring chemical properties to guide fertility in conventional and soil health operations is well-established (Haney et al., 2018; Hochmuth et al., 2014), but indicators which reflect the complex biotic interactions are still lacking, and it is these indicators which are needed to understand the holistic effects of implementing soil health systems (Fierer et al., 2021; Singh et al., 2024). Indeed, after reviewing one such indicator, the academic and producer researchers "collaboratively concluded that the expensive [PLFA] test results were not scientifically advanced enough to accurately represent the changes in the farmer's soil resulting from his adoption of cover crops" (Friedrichsen et al., 2021). Lacking quantitative indicators to describe soil health, producers in one focus group repeatedly mentioned qualitative assessments, but the authors cautioned that this should not be taken as evidence that they would not want quantitative indicators, if effective ones could be developed (Bagnall et al., 2020). An effective indicator would be responsive to short-term changes in management, such that producers could use the data from the previous years' experiments to guide decision-making for subsequent years. It would also need to assess soil function in a way that provides insight into the holistic functioning of the soil, the foundation of soil health (Natural Resources Conservation Service, n.d.).

This thesis describes social and soil science research done to address these challenges. In Chapter 1 of this thesis, I explored practical ways to elevate producers to co-researchers within the current land-grant university system of research. I used semi-structured interviews with 17 researchers (7 producers, 8 academics, and 2 non-academic soil health professionals) and descriptive thematic analysis to explore the question, "How can we reshape the relationship between academics and producers to improve collaboration and the co-production of knowledge?" In Chapter 2, I explored an on-farm soil health indicator which showed promise for being responsive to management. The tea bag index was developed by Keuskamp et al. (2013) as an accessible tool which could directly measure decomposition, an integrative ecosystem function. My overarching goal was to evaluate if measuring decomposition via mass loss of readily available substrates would be sensitive to producers' single-season, farm-specific changes in management, and if these tests can be performed by land managers using only materials available to them commercially. By incorporating social and soil sciences, this thesis explores multiple avenues to improve the ways in which academia can support producers innovating in soil health.

Chapter 2

Who will answer their questions? A qualitative analysis on supporting the research needs of producers innovating in soil health

2.1 Introduction

When implementing soil health on a working farm or ranch in the US High Plains, there is no recipe to follow. Instead, regenerative producers face thousands of macro and micro-decisions when translating general soil health principles into specific practices for their agroecological systems (Hansson, 2019). A subset of these decisions can be informed by existing scientific knowledge (e.g. the effect of different cover crop mixes on arbuscular mycorrhizal fungal abundance and root colonization) (Jamiołkowska et al., 2018; Yang et al., 2011). However, producers also pose critical questions about agroecosystems that span multiple domains and scales, involve poorly characterized and complex systems, and are necessarily context-specific. Questions are often broad and cross-disciplinary as well as narrowly context-specific. In contrast, scientific research tends to inform the generalized effects of a simplified set of practices on soil health outcomes across a broader region, leaving many producers' questions unanswered and under-represented in the literature (Gomiero et al., 2006; Rust et al., 2022; Singh et al., 2024; Vandermeer and Perfecto, 2017; Waithaka, 2005; Wood et al., 2014). Therefore, the producer must engage in their own research to determine how best to meet the soil health principles in their specific context.

The NRCS defines soil health as "the capacity of the soil to function as a vital living ecosystem that supports plants, animals, and humans," (Natural Resources Conservation Service, n.d.) and it is this functioning that soil health researchers (academics and producers alike) are trying to modify. One reason this is challenging is because the conceptual understanding of what underpins and modifies this 'functioning' is still developing (Bruyn and Abbey, 2003; Hansson, 2019; Singh et al., 2024). When researchers identify all the microorganisms in any given soil sample, the majority are novel organisms whose DNA has never been sequenced before. These organisms are yet to be named, let alone their functions within the microbial community mapped (Ramirez et al., 2014). Research throughout the last century has brought significant insight into the mechanisms at play, and high-throughput genomic methods are helping to continue to make major progress (Fierer, 2017). However, there is significant work required to translate any of this research into ecosystem services, which occurs when producers implement new practices on their land. Land-grant universities with extension networks are tasked with this work, but in many ways these systems fail to meet the needs of non-mainstream soil health innovators (Lobry De Bruyn, 2019; Waithaka, 2005). Academia has significant financial resources, labor, and specialized equipment which could be used to address these barriers, to better support soil health innovators.

Innovative models to improve the co-production of knowledge by collaborations between producers and academics are emerging. One particular model of note is detailed in Lacoste et al. (2021). This model calls for the producer to be respected as a co-researcher, instead of just implementing demonstration trials specified externally. Together, academics and producers define the research questions, specify trials, and implement them at scale. Everyone involved must grapple with the complexity that exists on-farm.

This study aims to improve the understanding of how land-grant university-based research does and does not serve the needs of the producer-researchers innovating in soil health in the High Plains. I performed semi-structured qualitative interviews with producers and academics working in soil health to understand if reshaping working relationships in this manner would encourage working more closely together on research trials, and what those relationships might look like to create positive research outcomes. I identified two key stakeholder groups: producers innovating in soil health, and academic researchers working in parallel on similar issues. These two groups are both blazing new trails in soil health research in their respective disciplines. Their insights will help us extend soil health research from the confines of the demonstration plot to large-scale implementation.

This article begins by providing context for the challenges faced by producers when implementing soil health practices, and reviews the literature about some of the current on-farm research paradigms. The empirical part of my study uses a qualitative descriptive analysis to explore data from interviews with three categories of soil health researchers: 7 producers, 2 professionals, and 8 academics. All researchers do applied work in semi-arid soils in the High Plains and inter-mountain region of the US, and most are actively engaged in soil health work specifically. The results section is divided into three parts: (1) the complexity inherent in managing a regenerative agricultural operation, (2) whether academia was seen as a source of support for producers who are navigating complexity, and (3) opportunities for highly collaborative on-farm experimentation to support producers. The discussion contrasts the findings in my study with literature on agroecosystem complexity, the gap between producers and academia, and the effectiveness of highly collaborative on-farm experimentation.

2.2 Literature review

Conventional agriculture in the High Plains is characterized by high levels of capitalization, increased use of monocultures, and heavy reliance on off-farm inputs for crop nutrition and pest management (herbicides, pesticides, and fungicides) (Altieri and Rosset, 1996). The ecological impacts of conventional agriculture include loss of biodiversity, eutrophication of waterways and greenhouse gas pollution (Aune, 2012; Gallardo, 2024). In response to this, many producers are investing in their soil health in a movement called Regenerative Agriculture. While consensus has not yet been reached on the definition of Regenerative

Agriculture, Sands et al. (2023) defines it as "a way of farming comprised of entangled values and practices, and founded in Indigenous principles of loving-caring for the Earth. This approach to farming values 1) reciprocity, 2) respect, 3) collective (human and non-human) well-being, 4) knowledge co-creation, and 5) (re)localization." In contrast to conventional agriculture which relies on simplified mechanisms to meet plant needs (e.g., synthetic fertilizers for nutrients), regenerative agriculture relies on complex ecological interactions between biological actors to generate its own crop protection and to transform non-synthetic inputs (e.g., legumes, compost, or manure) into plant-available fertility (Altieri and Rosset, 1996). The term 'ecological complexity' describes a complicated ecological system which cannot be simplified into smaller parts to study in isolation, without breaking essential properties of the whole (Vandermeer and Perfecto, 2017). As Levins and Lewontin (1980) describe it:

> It is not that the whole is more than the sum of its parts. But that the parts acquire new properties. But as the parts acquire properties by being together, they impart to the whole new properties, which are reflected in changes in the parts, and so on. Parts and wholes evolve in consequence of their relationship, and the relationship itself evolves... One acquires its properties from its relation to the other [and] the properties of both evolve as a consequence of their interpenetration.

To build a complex agroecosystem which can cycle its own fertility using non-synthetic inputs and support its own crop protection needs, most practitioners focus on improving soil health using the 5 soil health principles: minimizing soil disturbance, increasing cover, increasing diversity, increasing living roots, and optionally integrating livestock (Natural Resources Conservation Service, n.d.). These principles are applicable across very diverse eco-regions. However, there is a large gap between these generic principles and the staggering number of variables that a producer must address when implementing a practice. This gap is a fractal: for every decision made when implementing a soil health principle, there are countless combinations of eco-regions, operation types, equipment, and marketing opportunities into which it needs to fit. Researchers are trying to address this gap by doing more on-farm research in collaboration with producers (Honeycutt et al., 2020; Rossi et al., 2023; Walder et al., 2023), especially with participatory action research (Luján Soto et al., 2021; Nimmo et al., 2023; Sachet et al., 2021). But the progress made by this research pales in comparison to the sheer diversity of variables and situations that would need to be accounted for when implementing soil health on-farm. There is inadequate data to inform these decisions in sufficient detail to replicate between producers (Bullock et al., 2019; Roesch-McNally et al., 2018; Yuan et al., 2021).

The burden, then, is on regenerative producers to bridge the gap from the 5 generic soil health principles to the day-to-day soil health management decisions that work on their farm. Producers must do their own on-farm research to discover combinations of practices that work in their systems to build soil health, while still maintaining profitable operations. Producer-researchers offer a substantial untapped potential of time, experimentation, and creativity in how to apply the soil health principles to myriad contexts. It is this kind of distributed, big-data approach that would be needed to generate the body of knowledge that producers lack when they raise doubts about the viability of the soil health practice for their particular location (Brown, 2018; Lee and McCann, 2019; Lemke et al., 2024). However, this type of research has not been generally accepted in academia to date (Ebitu et al., 2021; McKinley et al., 2017; Ryan et al., 2018), because it has less randomization, replication, control, and peer review than a typical academic research trial. Even where producers, researchers and extension professionals are conceptually aligned, they often conceive of systems differently (Agroecology Summit 'Outside Empire' Subgroup, 2024; Blesh and Schipanski, 2024; Lash et al., 1998). Researchers interested in regenerative agriculture are divided between cultures, and both approaches have shortcomings. Producer research generally has insufficient rigor to discern anomaly from reproducible phenomenon, while academic research is not happening at the scale and complexity that producers face.

2.3 Research design

2.3.1 Research questions, data collection and thematic analysis

Our core research question was: "How can we reshape the relationship between academics and producers to improve collaboration and the co-production of knowledge?" To answer this question, our team conducted qualitative semi-structured interviews with 17 soil health researchers in the High Plains and inter-mountain region of the US. Of these 17, seven were producers with farms ranging from 0.7 to 2000 ha, all of whom are currently experimenting with more than one soil health practice on their operation every year. Eight were academic researchers from land-grant institutions, comprising a mix of extension and research faculty, ranging from 100% extension to 100% research. Two were non-academic soil health professionals. Interviews were conducted between 17 October 2025 and 18 March 2026. Joni Mitchek, coordinator of the Colorado Conservation Tillage Association, conducted the interviews with producers, and I conducted the interviews with academics and professionals.

We used purposive sampling to recruit interview subjects. We sampled producers who are actively engaged in soil health research and who are currently or had previously participated in a collaborative on-farm experimentation project, both projects having been jointly administered by the two interviewers. Five of them used to manage using more conventional methods, and 100% of the producers we contacted accepted the interview request. We sampled from academic researchers and professionals based at all major land grant institutions across the Great Plains and Mountain West region, who are actively engaging in applied and/or soil health research with producers. There is a possible self-selection bias as only 26% of the academics we contacted accepted the interview request. All interviews were conducted remotely and recorded using videoconferencing software, transcribed using an in-house transcription tool that uses Mistral's AI transcription tool (Vitullo, 2026), and checked for accuracy against the audio. Personal information was redacted to anonymize the transcripts. Interviewees were identified with a label (F = producer; A = academic or professional) and serial number (1-7 or 1-10). Prior to the interview, we sent some information about highly collaborative on-farm experimentation to the interviewees. We sent a peer-reviewed journal article (Lacoste et al., 2021) and a one-page summary of that journal article, as well as a high-level preview of the interview guide.

The semi-structured interviews consisted of three parts, and we discussed them in an open-ended format with participants. We asked the academics and soil health professionals to describe the soil health research and experimentation they do, and to explain the work required of producers to adopt those practices, probing for additional dimensions as needed. We asked who producers would seek out for assistance when working through the challenges related to adoption, and probed for mention of academia. We then presented one on-farm experimentation model (Lacoste et al., 2021) and discussed reactions, hesitations, and interest in such research. The interview structure for the producers was similar, asking them about the soil health innovation that they're working with on their farms, and whether academia is a source of support, or soil health testing a source of information. The questions regarding the Lacoste et al. (2021) on-farm experimentation were the same. All work was done in compliance with IRB protocols at Colorado State University.

I transferred the interview transcripts to QualCoder (version 3.7), a qualitative research analysis software package that runs on Python (Bogel, n.d.). I used an iterative process of coding the data, starting with open coding to capture labels, descriptions, and sentiments. From this I constructed themes through an iterative process involving coding to select and compress primary data, grouping into themes, and rearranging and regrouping into a coherent narrative. While this work was performed by the primary author, the other interviewer reviewed this work to ensure it was aligned with what she heard during the interviews. Throughout this process, the primary author kept a reflexive journal to document their decision-making process and to ensure transparency.

2.4 Results

2.4.1 Managing a regenerative system is more complex than managing a conventional one

2.4.1.1 "Mother nature, take the wheel!" and managing through biological proxies

Some of the regenerative producers want to work in a system where they don't directly influence primary characteristics of the system such as nutrients, but instead work through biological proxies to achieve the same functions. Sometimes this is phrased as working with Mother Nature, instead of against her. For example, instead of directly supplying nitrogen fertilizer using manufactured products purchased at the co-op, some producers have the goal to restore the natural functioning of their soils to enable the soils provide their own fertility. Producers described these practices as being more complex to implement and sustain than the equivalent conventional practices.

> Your biology, your biological nutrient cycle, that stuff's not working, but you just mask it by dumping this other stuff in to take its place. When you take that stuff away, then you see [how well your soil is functioning]... Instead of adding the nutrients themselves, support the system that will do that for me. And in the long run, that's going to save me money. (F2)

Instead of purchasing a tank at the co-op, producers are faced with restoring soil function across an entire landscape, and working through all the physical, chemical, biological, and ecological soil issues that are preventing the soils from functioning as well as desired. There's no simple "more" button to encourage biological processes, like there was with nitrogen, phosphorus, and potassium (NPK) fertilizers.

> It's a process. It doesn't happen [right away]. And the NPK thing gets them in the mind-set, I just put a little more fertilizer, I get a little more yield. It's immediate gratification. Whereas you go to this other route, building biology, and you've got to get your organic matter up, and you have to do all these things, that takes a while. (F1)

Neither is there a simple "less" button with biology. One producer is in a region with a new devastating fungal disease, and explained that he fielded phone calls from other producers asking about applying the agronomist-recommended fungicide:

> So I don't know why they call me. Because I always tell them, "well, you know what my answer is going to be... You might have economic return this year, but... what have you done to your system for next year, and in the following year?" [The other farmer asks,] "God, what if some of that fungicide hits the soil? Don't I want that? Don't I want fungi in

> the soil?" [F4 responds,] "Well, what do you think?... If it makes you money this year, what's it going to do? Are you now having to use it every year because you have a less healthy system [after using the fungicide]?" (F4)

This work requires holistic learning, and listening to what Mother Nature is telling them, and responding in a way that continually shepherds the system towards one of greater health and soil function. Some interviewees contrasted this with the more conventional practices they used to manage with, and remarked on how much more complex soil health work is. Some producers feel alone in this journey, and that academia isn't thinking holistically with them and isn't helping them address their systemic issues with solutions that don't disrupt the rest of the system. They do not just want a quick fix.

> But [tillage, a quick fix offered by academia/extension,] ignores the fact that [the perennial] grass is telling me that my system is flawed. It's telling me something. It's speaking Greek, and I don't know Greek. I expect my extension or academia or somebody there to speak Greek... [the damage caused by one tillage operation could] take another 10 years to [restore], and it would not fix the problem because the grass will be there next year. (F1)

2.4.1.2 Managing diversity means you have diverse things to learn and manage

Managing biological systems requires a lot of care-taking work, making sure that all the living entities are fed and watered. Many producers described the challenge of keeping up with the needs of all their living entities:

> I have biology going and I'm not feeding it. So the only thing it has left to eat is my residue. And it's just devouring my residue. So if this no-till is going to work, I've got to go about this differently and manage my biology better because it's just kind of working against me at the moment. (F2)

To be a producer in the US today, whether that's conventional, regenerative, organic, large- or small-scale, requires filling many roles. Each producer strikes their own balance between in- and out-sourcing the work, including roles such as equipment mechanic, bookkeeper, crop disease specialist and logistics professional. However, regenerative producers have additional roles to fill because of the diversity of their operations. Sales and marketing might be needed unless markets already exist in the region for the specialty crops they grow. Some are their own agronomist, unless they're lucky enough to have one they are conceptually aligned with.

> You just have to be your own advocate. You have to know what you're doing and go in and just tell your supplier, "I want this. Don't ask questions... If you want to know, I'll tell you, but you're going to think I'm crazy." (F3)

When managing risk on their operations, some producers do this without the benefit of some USDA programs because their diverse practices have excluded them from the programs. They navigate additional RMA regulations compared to conventional neighbors, to ensure their practices are allowable with crop insurance, and are sometimes disqualified nevertheless. They navigate how to access cost-share programs, with added layers of complexity if they're on tribal lands. They procure and maintain specialty equipment, and do infrastructural projects to support the diversity of their operations.

> We're going to... renovate some of the small bins that were just kind of abandoned with cone bottom. Because all we have right now are really big bins, 20,000 bushel bins, which are awesome when you're growing wheat/corn and you have a whole bunch of two things. But the more diversified I get, it becomes a real problem... You know, you see that the headlines are always cover crops or livestock integration. Nobody talks about, you know, bulldozing around the bins to change traffic flow... I think 100 years ago, [this farm] was kind of set up for that kind of thing. But as the years went by, things became more commodity driven, just big scale, less diversity. (F2)

Most of the producers consistently mentioned how much there is to learn in the field of soil health, and that the more they learn, for example, through soil health conferences and field experiments, the more questions they have. Even generational farmers, who grew up in an agrarian culture replete with agricultural ceremonies, expressed how they are continually learning from the land, and that the learning never stops (F5, F7). But learning takes time. One producer wanted to find a less synthetic, less expensive alternative to slow-release fertilizer, and a speaker at a soil health conference suggested trying soybean meal. Thousands or tens of thousands of hours of engineering optimization happened in the background to bring a tote of slow release fertilizer to the co-op, including embedded intellectual work for agronomic performance, practical considerations for application, and technical support when things go sideways. Stepping outside of the agribusiness model (eg by using soybean meal instead) also means losing out on all that accrued knowledge and taking on one's own intellectual burden (F6).

2.4.2 Academia was not a source of support to address complex challenges

While these producers navigated complex challenges, they rarely (if at all) mentioned academia as a source of support:

> I guess we've just kind of let the university system do its thing. . . . I just haven't found too much value in paying attention to it. You know, not that what they're doing is bad. It's just not what I'm looking for. (F3)

Academia was even seen as a detriment.

> I feel like academia. . . needs to be leading us and pulling us along instead of holding us back, you know? (F1)

This was equally true of extension. Recalling his working relationship with his extension agent, one producer mentioned:

> But when it came to soil health, really thinking out of the box and trying to be innovative and big picture with things, I didn't feel like his brain worked that way. Just very university trained. So it's been a very long time since I've had a soil health conversation with him. (F2)

This attitude was prevalent throughout the interviews we conducted. Five of seven producers had been involved with a large, highly collaborative on-farm research project, run in conjunction with two land-grant universities. The other two were not part of that project but were participating in the smaller follow-on collaborative research project run out of one of those universities. Nevertheless, producers described a gap between their research interests, and the research being produced by the universities, research stations, and extension.

2.4.2.1 There is a gap between the questions producers have, and the research questions that academia studies

Many producers are managing their operations in a holistic manner and thinking about systems-level questions. The research questions they are asking are at once broad and multidisciplinary, while also narrowly specific to their own ecological context. As a few of the academic interviewees remarked, system-level considerations are not always framed as a research question:

> What are we actually trying to find out? Is it just a factor of yield? Or are we looking at profitability? How does something shift microorganism life in the soil. And it could even be sort of crop specific. How does a certain biological work on corn versus something else?. . . But again, I think it has to be systems-based and not just one product versus another product. (F3)

> I'm not a fan of corn. I was trying to find a way out of corn... Really trying to find a way to get to a more perennial system without just, you know, just being a ranch. (F2)

> And to create a symbiotic relationship with the plants, you have to have good microorganisms and a good, healthy, diverse ecosystem underneath the soil... you create an environment to keep that topsoil down and you're keeping those microorganisms in the ground healthy and happy. (F7)

> Existentially, can we do this forever, what we're doing now? That was always kind of my interest as a kid is, wow, what we're doing here, is that going to work in 50 years, you know, when I was witnessing soil erosion and all that. (F4)

What they often boil down to is "What could I change in the system to make that function better?" This is not a typical academic research question, and is moreover hard to answer. In contrast, the standard Western scientific method requires a distillation of the system under study to a few component parts, to understand the underlying causal links. These research projects each shed a sliver of light on a specific mechanism, which might one day build to a holistic understanding of the system – but science does not yet have that holistic understanding. Describing soil health research, one professional said:

> So when we use practices this way or that way, because they're so context dependent, I think it's easy for people to discount and say, "well, yeah, never can tell with soil health". And because we're generally ineffective at describing what was the context... that's a big limitation in trying to understand... the factors that made it go one way or another in [productivity and soil health metrics]. And that's an inherent limitation in science. And in science communication. (A1)

The soil health research that the academic interviewees described were in alignment with this distilled-to-the-elements method. One studied cover crop mixes, trying to parse out the effect of separate functional groups. One was a study of two fertilizer rates across nine crops. Two of them studied the soil health benefits of leaving stubble tall (corn in a silage study, wheat in a stripper header study). However, some producers struggled to identify the utility of academic research projects to their complex and interacting systems, expressing skepticism with research when done in this way.

> But then again, even the single factor analysis on a farm, there's so many moving factors and moving pieces to this. And this is more about systems rather than practices. So it's a little difficult to pinpoint. Did this one small change really make this difference? (F3)

2.4.2.2 A rift between academia and producers

Soil health research models often fail to capture complexity that is acknowledged by academics. One academic described implementing cover crops, and mentioned challenges with timing the covers around the cash crop, fertilizer needs, grazing and termination strategies, and weed seed management, then paused and said, "And so to me, there's not a lot of considerations, except there's the. . . ." and continued to list challenges with economics, impacts to yields, interaction between economics and grazing, and water and nitrogen dynamics (A4). From the producer side, the discrepancy leads to the feeling that academics can ignore that complexity in the name of some more abstract intellectual pursuit.

> That's kind of where academia... can fall into the trap of elitism. I've got a PhD. I'm smarter than you. And you are, but you're not because I'm making it work. You know what I'm saying? If you were smart like you are and you had a 3,000 acre farm and it was working, now we can talk. You see what I'm saying? I can sit in academia in my classroom. I got no skin in the game. I can say whatever the hell I want. (F1)

Instead, all the producers we interviewed looked to alternative soil health experts and successful soil health peers, before going to academia. While reliability can be inconsistent, the credibility of findings from a soil health experiment increase dramatically if that experiment was funded by a producer with 'skin in the game' (F1, F2, F3), as opposed to academia. If an academic runs a research project and the results aren't as good as anticipated, there are few negative consequences for the researcher. This starkly contrasts with producers who are self-funding research into new management practices. If their experiment doesn't work, they cannot reframe it with better statistics or a simple "more research is needed. . . " statement. Their livelihoods are on the line. As one producer noted:

> And so we just got so fed up with them. You know, poo-pooing on rotational grazing. So I've got these PhD's telling me it doesn't work, and then I've got these ranchers telling me it does. Well, who am I going to believe? Not the PhD's. They get paid either way, whether it works or not. The ranchers say, I almost went broke. Now, I'm not. So, you know, they got skin in the game. So that's who I believe. (F2)

While producers find this research credible, academia often does not, because the research often does not meet the standards of the Western scientific method (A2, A7, F1). When producers shared their research findings with academics and extension, they weren't taken seriously.

> But yet it's still met with this skepticism. It's plain as day what's happening. The results are there, but, well, [academia] can't really say that it's happening because it didn't fit [in their] experimental box. Well, that's not helpful at all, thank you. (F3)

2.4.2.3 Structural barriers to meeting producers halfway

Some academics sought to meet producers halfway by modifying their approach to research and asking questions of interest to producers. However, academics have constraints that drive their research decisions. For one, academics are often required to publish. Graduate students need to complete projects and publish the results to graduate, and professors' promotions are influenced by their publications, where both the quantity and the quality of the journal matter. In general, academics mentioned that on-farm research can often generate messy data, which is much harder (or impossible) to publish:

> It's definitely challenging from a research perspective. Like, you know, these are messy studies. One farmer changed his field halfway through. One farmer retired. One farmer's field got hailed out and he decided no more. So like we have not yet been able to publish this data. It's just really messy. We're kind of submitting to lower and lower tier journals... So the messiness is a big negative, especially for early career researchers. (A2)

Interviewees mentioned several sources of this messy data. It's harder to control for all the additional sources of noise when you're in a less-controlled environment compared to a greenhouse, or even a small plot on a research station. The details of the implementation are out of the control of the researcher. This is compounded when the producer is outsourcing field operations such as harvest to a custom operator, cannot calibrate the yield monitor, and does not have direct access to the data. On this front, one academic said:

> And what we found is the challenges of actually getting those practices implemented properly so you have good data because I think that's important... if it isn't done right, then it's just garbage. And that's not their fault. That's our fault... When academia does their own research, they control a lot of those variables. But it's just a lot harder when you're dealing with farmers, to be honest with you. (F6)

Academics mentioned that these projects often require a lot more labor to gather lower-quality data, and that the projects often move more slowly. Instead of dictating treatments to graduate students or employees on a research station, you have to manage many partners and balance their needs and time constraints.

Gathering management records from multiple busy producer partners is a perennial challenge. And if all this extra work is non-publishable, then it can feel demoralizing, as one professor describes after a recent on-farm research project:

> But if it's more research effort, my end goal is to get a publication out of it if I can... But if I spend a whole bunch of time working around and then at the end of the day you can't publish it, it becomes just like a little depressing. (A6)

There is the compounding issue of how academic salaries are structured. Unless academics have an extension appointment, research with producers represents a large workload that may not directly contribute to the growth of their career (A2, A6, A8).

Funding is also an issue, in terms of what funders consider legitimate and what conditions they place on research. It can be harder to get funding for on-farm experiments:

> 30 or 40 years ago, our faculty didn't have to scramble for dollars. The dollars came into the university so they could use them to do this type of work. That doesn't happen anymore. And so connecting an idea with a funding source is a real challenge. (A10)

Funding is often structured for 3-year projects, which producers and academics considered too short of a period for slow-changing semi-arid soils to show improvements in soil health. As one academic shared:

> Most funding cycles will be like three to five years. So you will finish your project without measuring any useful change. And then it becomes kind of a little bit depressing, right? You thinking that you're working on this fantastic project, then at the end of the day, you are not seeing what you think the results should be. (A6)

2.4.2.4 Soil health testing isn't helping answer the system-level questions either

If producers are not getting the information they need from academia, some producers are doing their own on-farm research. However, soil testing does not often provide clear answers. In this region soils change slowly, and climate can influence soils so much that it overwhelms any signal coming from the data. Moreover, because regenerative agriculture is characterized by hands-off management and indirect controls, there is less of a direct link between soil health tests and management decisions. Producers described how they are managing for the soil health principles in general, but we heard no instances of a producer articulating how soil health tests led to management changes, or even to insights into the functioning of their soils.

> I've done a lot of like the PLFAs and yeah, it gives you cool information, but it really doesn't really sway my management, I guess... It just seems like the results are never very consistent. I just don't put a lot of faith in them, I guess. (F6)

> But why is this area of the field doing better? It doesn't show on the grid sample. Things like that. And what could I change in the system to make that function better? (F4)

Instead, several producers pointed to more qualitative evaluations that helped them develop an understanding of how their management choices affected their soils.

> You know, we have data, but boy, just the observation of, okay, what we did this year, how has it affected our total system? And usually I'll learn what I could have done better. (F4)

Additionally, how the test results are delivered has a strong effect on how useful the data was, especially for new or complicated indicators. For the producers who mentioned it (F1, F2, F4, F6, F7), the gold standard was if the data was accompanied by a consultation with soil health experts. This created the opportunity for a dialogue supported by data, a brainstorming session with an expert to unpack what the data means and how to turn it into management decisions.

> Okay, there's a whole page of numbers, and there might be something interesting in there. But what I really need to know is what I need to go do. I'd be far more interested in the numbers... if somebody who knew all that stuff were to just sit [with me for a consult]... So, yeah, I mean, especially with this new approach that we're trying this year [genomic-based testing + product recommendations], I'll definitely want some explanation of what's going on. (F2)

2.4.3 Highly collaborative on-farm experimentation: producers as co-researchers

The research model presented in Lacoste et al. (2021) proposes moving beyond on-farm research as "just a demonstration" of things learned in the greenhouse. It specifically calls for producers to act as co-researchers in the project. Their model details how collaborative relationships can bring new innovations. These views were echoed by some of the researchers, both producers and academics, who described collaborative research projects leading to innovation.

> One farmer did his own test of interseeding, but there were just all these questions of like, can I interseed it? And it was like, "You could try. I don't know if anyone's done

> it before." But thankfully. . . it was so similar to practices they had done... Even when it often did mean going against conventional wisdom. The recommendations we got across the board were to fall plant. And the farmers that we worked with were like, no, I'm not going to fall plant it. I'm going to spring plant it. That's how I plant a similar crop, because that's when we have more moisture. And that was really successful. (A2)

This model of highly collaborative on-farm experimentation can be a vehicle to bring the resources of academia to the issues that the producer researchers face. Directly gathering producer-researchers' questions and addressing them in projects can lead to more systems-level questions and fewer projects studying isolated treatments. That said, such research needs to meet the needs of academics without extension appointments. Academics discussed conflicting success rates with publishing messy data, sometimes having to publish in less prestigious journals. Even so, several academics mentioned that difficulties were offset by other benefits of collaborative research.

> I think, you know, we may lose a little bit in terms of statistical rigor, experimental rigor, but the fact that It's research in practice, right? It's farmers trying to implement this and make it work. I think that adds value and maybe offsets in a large way [the added statistical rigor] you get in a controlled experiment. (A5)

2.4.3.1 Suggestions for implementing these projects, from veteran researchers

Numerous suggestions came from academic and producer researchers which are useful for professionals looking to implement collaborative projects. We present a few suggestions, including ones about building relationships, how to address the larger workload of such projects, and community-specific considerations.

Building strong relationships with mutual respect was mentioned often as a pre-requisite to good collaborations.

> So it's, it's taken a while to gain trust. I mean, I've been doing this for seven years and I feel like I'm finally starting to gain some trust. And it's taken a long time, but, and I have limited... So these guys are really busy and you've got limited time to interact. (A3)

> [Describing potential pitfalls] I guess individuals not getting along together very well. I guess, you know, a farmer personality and an academic personality, just not meshing very well. And the approaches, you know, maybe the farmer sees one thing, but the academic individual like sees [a different way of] how it could be done. And there's a miscommunication on what's all being sought after, you know, just kind of, I guess, communication would be super important. (F7)

Since time was cited as one of the major limiting factors by most researchers, several suggestions were centered around how to effectively create more time for people by adding personnel. One academic expressed wanting to hire an administrative coordinator to help with the vast amount of administration work that was needed in the project, which otherwise fell onto him and his colleagues.

> So it was like more work than I ever did. And some of it was not fun work... organizing everything from food to, you know, porta potties at field days and everything. So I was like, oh my gosh, this is how it should be done, and then I'm not sure I'll find the energy to ever do that again. So it was the good and bad of heavily collaborative research. . . In retrospect, it would have saved a lot of energy if we had had a support person, like almost full time for that project. (A4)

Three producer researchers discussed the benefits of having a research assistant to do the data collection on their field, describing how the added time of research might not fit into their already too-much workload.

> Then I know it's not on me to [take the soil samples], and oh, I got to get this soil in the freezer. And I got to go pull a calf. So do I go pull a calf or do I put the sample in the freezer? (F2)

One mentioned the added benefit of increased accountability, describing how it would be motivating to have to not disappoint a person who was, in the end, just trying to help him do the research that he wanted to do in the first place.

> The whole point of the study was something that I wanted the answer to. So why would I not go do that? So, yeah, to have a. . . research assistant or whatever you want to call them, somebody you knew personally that could say, hey, I'm going to be down on Thursday. Any chance you got that thing done? You say, oh, boy, I'll go get it done right now. So, yeah, I could see that helping. (F2)

Outside of these interviews, another producer mentioned that his peer group had discussed hiring such a person independently. They added that if the candidate also had agronomy background it might bring enough value to make such a hire possible. Another mentioned observing the in-depth sampling and testing done by a non-academic soil health group, and being thankful that work wasn't falling to him:

> We went out to see him. I mean, that man was running from his infiltration tests and stuff. And it's like, I'm not sure I've got the energy to, and A, I don't have the energy, but

> B, to do it right, you know? And so I think he's going to be doing all the tests. Which is good. (F1)

Lastly, there might be community-specific restrictions to work around, as in the case of two producer researchers from a tribal community. Good, open communication is critical to ensure that all partners' requirements are being met:

> For our community, you know, we live in a closed community. So there are days where people that are not from the community wouldn't be able to get in and have access. It wouldn't be like an open access thing, you know, like our field would not have complete open access... [So for planning field work, he might have to say,] oh, I'll have to let you know as time goes on, you know, but tentatively, yes, plan on coming out. If that doesn't work out, then we'll have to reschedule. (F7)

2.4.3.2 Researchers in the High Plains are hungry for more of this kind of research

When asked if they were interested in being a part of more highly collaborative on-farm research project, where producers were treated as co-researchers, the response ranged from overwhelmingly positive to slightly on the positive side of neutral for 100% of interviewees.

> Well, you know, in a way, we kind of do a research project every year on our farm. We're trying something new. We're innovating. . . Yeah, but I'm not going to sit here today like, yes, I'm really excited to do a major research project this year. Well, not really. Not just looking to go do that this year unless there was the opportunity that was like, no, this is very valuable to us. And we want to measure this and improve this. (F3)
>
> [After being asked if they would agree to another round of a highly collaborative OFE project] If we kind of [frame it as] more of an extension kind of work, because if you are doing research, the data that we are getting, we may not be able to publish it. Then it becomes like an outreach kind of an effort. But yeah, I'll be more than willing to do that [again] because I do have an extension appointment [now]. (A6)
>
> You know, most of what we do, I do, in the academic world is controlled settings and they don't often don't apply or apply directly to a working farm. And I think that's where a lot of our research gets lost in translation. It's just... You know, we can do it when we isolate things and in a small way, but when a farmer tries to do it in a larger way, sometimes it just doesn't work. And so I think it's a sacrifice that we lose a little bit of that rigor, but I

think what we're doing, the things that work, that farmers see work, they're going to use them. And they're telling friends and neighbors about them. And neighbors are seeing it, you know, on their farms. And so I think that will offset the experimental challenges. (A5)

Honestly, I wish we were doing more of it. (F6)

I'm a 100% advocate for on-farm research. At least in this part of the world and at least with biology, because the lab or in a research, you know, 8x12 plot or whatever, I just, you can't replicate the reality there... Having been through [a positive OFE experience], seen it all happen, and seeing guys like that [i.e., skeptical academics] get an awakening, I mean, I'm like, this is the only way. This is the only kind of research you need. (F1)

And the experience, when it goes good, can be phenomenal. And each of those team members, not only in developing what the project's going to be, can learn new things beyond what they expected to learn from the interaction. But you can get a lot of work done, and it becomes an enjoyable experience, not drudgery. So when it goes good, it's great. (A1)

2.5 Discussion

In alignment with previous work, the producers in this study described how complex it is to implement successful soil health systems in the High Plains. They also emphasized the complexity of managing whole systems instead of individual factors in isolation, and viewed issues as symptoms they could use to understand the functioning (or lack thereof) of the larger ecological system. Previous studies noted that there is no guidebook for managing a complex suite of goals when implementing soil health practices (Jackson-Smith et al., 2018; Klein et al., 2024), and producers emphasized the importance of biological indicators (Klein et al., 2024), collaboration with ecological systems, systems thinking, and descriptions of self-organizing systems that built on each other towards a more functional landscape (Gordon et al., 2022; Jackson-Smith et al., 2018). Producers' own knowledge systems in this and previous studies tended to be holistic, and explicitly incorporate the complexity inherent in the system. However, these knowledge systems have not always been valued in academia (Blesh and Schipanski, 2024; Klein et al., 2024; Lacoste et al., 2021), whose underlying knowledge system (e.g., Western science) can be reductionist and linear.

This mismatch in knowledge systems reduced the credibility of academic research for the producers in this study, who pointed to academia's simplified abstraction as a fatal shortcoming. Academia frames the outputs of experiments primarily through statistics which suit scientific orthodoxy, but results framed in this way are not always interpretable or meaningful to producers (Lacoste et al., 2021). Further, multiple studies on the same topic can have conflicting, statistically significant results. To make sense of such research is challenging, and not many producers in this study ascribed credibility to the findings in those types of studies. Instead, when defining highly credible research, the producers pointed to other producers experimenting with new soil health practices who have built financially and ecologically stable agricultural operations. This is echoed strongly in the literature, where peer-to-peer information was found more trustworthy than extension or academia (C. R. Anderson et al., 2019; Lacoste et al., 2021; Rust et al., 2022). In addition to this, previous studies found that producers are increasingly less satisfied with the traditional information transfer of land-grant research findings, which is typically one-directional: from academia, mediated by extension, and delivered to producers (Klein et al., 2024; Pires et al., 2024; Rodgers et al., 2026; Waithaka, 2005). the interviewees strongly echoed these sentiments, describing a dearth of technical support from these entities in topics relevant to them. However, land-grant research and extension are tasked with delivering support to all producers. The soil health innovators in this study are the minority in their regions, and it is perhaps not surprising that the majority of the land-grant support is delivered to the majority of producers (i.e., more conventional producers).

Resulting from this perceived lack of support, many of the producers in this study turned to doing their own research to understand the holistic effects of their soil health practices. However, these efforts were hampered by few quantitative tools to help guide that research. Current soil health tests are typically measuring single factors at a time, and are often not sensitive enough in semi-arid soils to show meaningful changes in short timescales (Bruyn and Abbey, 2003; Klein et al., 2024; Singh et al., 2024; Victoria et al., 2025). The producers in this study were aligned in their assessment of commercial soil health indicators, describing their utility in measuring limited single factors, but not useful in describing holistic or systems-level changes in the functioning of their soils.

Therefore, academia needs to find new ways of collaborating with these producers innovating in soil health, and learn how to co-create knowledge. Researchers are calling for integrated and participatory approaches which balance reductionism and holism to co-produce knowledge (Blesh and Schipanski, 2024). The proponents of such approaches point to the benefits of fostering processes of inquiry, the value that academia can add with specialist skills or external perspectives, and argue that this model leads to innovation, not mere diffusion of static information (Lacoste et al., 2021). Producers' own experimentation is happening at a scale that drastically exceeds land-grant funded research, which creates an opportunity for massive replication across myriad soil types and climatic conditions (Hansson, 2019). I found strong support for such research in this study, which aligns with several previous studies (Jackson-Smith et al., 2018; Lacoste et al., 2021; Pires et al., 2024). However, many interviewees in this study had strong opinions about how challenging and time-consuming collaborative research is. One recent study, which is currently in press, details some of the challenges that can arise with this type of research, and provides guidance for how to shape the project to best address the needs of all the collaborators (Rodgers et al., 2026). These include aligning the project to meet the goals of both researchers and producers, additional resources and time allocations needed, experimental design, and managing risks. A strong theme in the literature and in the findings from this study was the role of trust and relationship building, prior to the initiation of the project (Blesh and Schipanski, 2024; Rodgers et al., 2026; Rust et al., 2022). Ideas related to these challenges and complications of on-farm research, and especially highly collaborative on-farm research, were raised by 100% of the academics we interviewed, and nearly half the producers. This is challenging work, and in some cases structurally thankless work. Despite this, there was overwhelming support for more highly collaborative on-farm experimentation.

2.6 Conclusions

This study examined the viewpoints of soil health academics, professionals, and producers in the semi-arid High Plains and inter-mountain west of the US. Three themes emerged from interviews: (1) managing a regenerative agricultural operation is perceived as more complex than managing a conventional one because producers are managing ecological systems to be self-sufficient and built holistically. (2) Producers did not mention academia or soil health testing as a resource to address the complexity of regenerative agriculture. Academics face structural barriers to supporting producers in the ways in which they might want to. (3) Highly collaborative on-farm research was lauded as a powerful tool which all participants valued, and wanted to be more involved in. In closing, all researchers anticipated issues with on-farm research, including building trustworthy relationships, finding the time, and balancing workload commitments. Therefore, finding solutions to sustainable agricultural operations in the High Plains must be a team effort. By coming together, soil health researchers can ask better questions, run better experiments, and build realistic pathways for broader adoption of soil health practices across the landscape.

Chapter 3

Supporting regenerative producers with responsive on-farm testing: tea bag decomposition and aggregate slaking are not sensitive to single season on-farm experiments

3.1 Introduction

When implementing soil health on a working farm or ranch, there is no recipe to follow; instead, regenerative producers face thousands of macro and micro-decisions to translate general soil health principles into specific practices for their agroecological systems. Here, we define soil health as “the soil’s capacity to function as a living ecosystem” (Natural Resources Conservation Service, n.d.). A subset of these decisions can be informed by existing scientific knowledge, through the traditional extension model of a one-way knowledge transfer from researchers to producers. However, this knowledge transfer model has long been inadequate to address farm management complexity (Waithaka, 2005; Wood et al., 2014), particularly for producers with questions about agroecosystems that span multiple domains and scales, involve poorly characterized and complex systems, and are necessarily context-specific. For example, one producer asked, ”how can I build residue on my soil surface, now that my soil microbiome is cycling through it faster than I can build it? Without residue, germination suffers; without germination, residue suffers.” (S. McFarland, personal communication, January 13, 2026) These types of questions are extremely broad and cross-disciplinary as well as narrowly context-specific. In contrast, scientific research tends to evaluate the generalized effects of a simplified set of practices on soil health outcomes across a broader region, leaving many producers’ questions unanswered and under-represented in the literature (Gomiero et al., 2006; Singh et al., 2024; Vandermeer and Perfecto, 2017; Waithaka, 2005; Wood et al., 2014). Therefore, the producer must engage in their own research projects to determine how best to adapt and apply the soil health principles in their specific context.

To navigate the complex decision tree when translating from generic soil health principles to detailed implementation plans, producers often experiment on their own fields and use soil health metrics to measure success of the experiment. However, identifying responsive metrics to assess soil health impacts of on-farm experiments has also proved challenging. Soils change slowly and indicators of soil function tend to be highly variable in space and time (Hartmann and Six, 2023; Robertson et al., 1988; Semenov et al., 2025), semi-arid soils even more so (Lal, 2004; Wienhold et al., 2006). For example, soil organic carbon (SOC) is a cornerstone of soil health, but it can take more than a decade to measure significant changes in semi-arid soils (Lal, 2004; Semenov et al., 2025). Along with SOC, other key soil health indicators include potentially mineralizable carbon (also known as CO_2-burst or soil respiration) and aggregate stability. These indicators have been suggested as a minimum suite of soil health tests due to the functions they are intended to measure and their sensitivity to long-term soil health experiments (Bagnall et al., 2023; Franzluebbers et al., 2000; Liptzin et al., 2022). However, these indicators are all spatially heterogeneous due to highly variable factors such as soil texture, aspect and slope, water dynamics, and bulk density. For a null result, it is impossible to disambiguate whether these indicators are not changing at all, or if the changes were not detected amid the background variability (Conant et al., 2011; Jandl et al., 2014). The challenges of low signal-to-noise ratio indicators can be overcome using long-term experiments (e.g. a decade for SOC) or large sample sizes to build signal strength in the indicator. However, if producers aim to use the data from these experiments to drive future management decisions, rarely can they wait a decade or invest in extremely large sample sizes to understand if their previous management changes are resulting in soil health outcomes.

Thus, quantifying the soil health effects of producers' experiments requires an indicator which is sensitive at a relatively small number of replicates on one field after single-season or shorter-term changes in soil health. Today, there exist few to no quantitative soil health metrics that are this sensitive, other than yield (Doran and Zeiss, 2000; Miner et al., 2020). Emerging molecular techniques to assess microbial communities and diversity such as high-throughput sequencing show promise to be more sensitive to management changes (Fierer et al., 2021). However, they are characterized by extreme spatial and temporal variability driven by stochastic effects (Borer et al., 2018; Hartmann and Six, 2023), limiting their utility in assessing the outcomes of soil health experiments. Furthermore, while high-throughput sequencing has advanced the science of describing communities and diversity, there is still a gap in linking this knowledge to microbially-mediated soil functions (Fierer et al., 2021). Until microbial communities can be easily and consistently linked to functions, indicators which infer function may be more useful, such as decomposition and soil aggregation.

Decomposition assays quantitatively measure a major function of soils (rate of decomposition), which is indirectly linked to microbial biomass, functional diversity, and activity. Decomposition in soils drives global nutrient cycling and soil fertility, is responsible for more than 90% of the energy flux in soils, and is a critical step in the pathways to creating soil organic carbon (Barel et al., 2019; Cotrufo and Lavallee, 2022; Hartmann and Six, 2023). Decomposition assays have been shown to be highly sensitive to changes in management such as incorporating crop residue, nitrogen inputs, tillage, and perennial cropping (Gmach et al., 2024; Houben et al., 2018; M. D. McDaniel et al., 2025). While climatic variables drive decomposition rates to a large extent, increased decomposition is expected for soils with greater microbial activity. Recently, the tea bag index was proposed as an accessible decomposition assay for a participatory science effort to compare soil carbon cycling across global ecosystems (Keuskamp et al., 2013), and the tea bag index was further adapted for on-farm use to assess soil health (M. D. McDaniel et al., 2025; Middleton et al., 2021). Specifically, the decomposition of green tea in producers' fields correlated better to yield than lab-based microbial analysis (Middleton et al., 2021).

However, some critical limitations still exist in the accessibility of the tea bag index. The original tea bag index methods specify the use of nylon tetrahedron bags (EAN: Green 87 22700 05552 5 and rooibos 87 22700 18843 8) but they are no longer available for purchase. Replacement tea bags should be resistant to biodegrading, readily available to producers, and should have a mesh size similar to the nylon tetrahedron bags used in previous studies (0.25mm) (Keuskamp et al., 2013; Middleton et al., 2021). Previous studies acknowledged the high percentage of leachable fraction in the decomposable substrate (up to 28%) (Duddigan, Shaw, et al., 2020; Keuskamp et al., 2013; Middleton et al., 2021). This fraction could leach from the substrate in variable amounts dependent on the ambient soil moisture, potentially increasing within-plot variability. Soil contamination in samples is a well-known issue in litter decomposition studies. The ash-correction method is a common solution, using a high-temperature muffle furnace (Potthoff and Loftfield, 1998), but producers generally do not have access to laboratory-grade furnaces. Other methods have been proposed, including the moisture equilibration technique (Herrick, 1995), control bags with non-decomposable substrates which become similarly contaminated (Idol et al., 2002), or washing (Potthoff and Loftfield, 1998). Similarly, producers often don't have access to laboratory-grade analytical balances, but low-cost, consumer-grade scales exist at online retailers. Finally, some methods involve using multiple decomposable substrates (Duddigan, Alexander, et al., 2020; Keuskamp et al., 2013; Middelanis et al., 2023) or removing substrates sequentially to develop a time series of decomposition (Middelanis et al., 2023; Mori, 2022a, 2022b). In practice, the labor to build, retrieve, and wash substrates becomes a limiting factor, and producers might opt to save labor and install fewer replicates. One of my objectives with this study was to refine the tea bag index methods for use by producers by improving accessibility and reducing labor.

Water-stable aggregation is a second indicator that shows promise in being sensitive to soil health management while remaining accessible to producers. Soil aggregation is a process by which mineral soil particles are bound into water-stable structures, typically mediated by soil microbes as they decompose organic material. Stable aggregates in soil improve water and gas exchange, reduce erodibility, and are associated with an increase in diversity of microbial communities (Rieke et al., 2022; Six et al., 2000; Wilpiszeski et al., 2019). Previous studies have shown that aggregate mean weight diameter as a metric of aggregate stability is responsive to management changes in semi-arid soils (Kelly et al., 2021; Noble Strohm et al., 2025; Rosenzweig, Fonte, and Schipanski, 2018); however, the protocol used in these studies is challenging and labor-intensive. By measuring the slaking of aggregates following rapid re-wetting using image analysis, the SLAKES smartphone app is accessible to producers. Indeed, it is one of the three indicators used by the Soil Health Institute in their Minimum Suite of Indicators (Bagnall et al., 2023; Fajardo et al., 2016; Rieke et al., 2022).

My overarching goal was to evaluate if measuring decomposition via mass loss of readily available substrates would be sensitive to producers' single-season, farm-specific changes in management, and if these tests could be performed by land managers using only materials available to them commercially. My three specific objectives were to: (1) improve upon the original tea bag index methods to reduce variability and make it accessible to land managers, (2) evaluate if the improved methods are sensitive to changes in soil health management, including single-season and long-term changes, and (3) compare the decomposition method with another accessible soil health indicator (SLAKES smartphone app) for relative sensitivity to these same management changes. I hypothesized that mass loss from decomposition would be greater in soil health plots compared to their control strips, in both single-season and long-term soil health test plots.

3.2 Methods

3.2.1 Overview

This study consisted of 4 experiments. In the first experiment I evaluated methods to adapt the Keuskamp et al. (2013) protocol to reduce variability by removing the leachable substrate and soil contamination using only resources available to producers (no analytical balance or muffle furnace). In the second experiment, I decomposed multiple household substrates in the laboratory (green tea, rooibos tea, cotton balls and cotton fabric) and selected the most sensitive substrate and incubation duration for further study. In the third experiment, I decomposed green tea in paired treatment/control plots at seven field sites for 31-34 days. In the fourth experiment, I used paired soils from 5 of the field sites and quantified green tea decomposition in a laboratory incubator across a time sequence (from 4 to 31 days).

3.2.2 Study Sites

Sites included five working farms with either long-term or single-season, farmer-defined soil health experiments and three research stations with existing long-term soil health experiments. All sites were within the High Plains. The research station soils with long-term controlled experiments were selected to contrast with the shorter-term or single-season on-farm experiment soils with similar climate and irrigation regimes.

Long-term experiment sites included the CSU Agricultural Research, Development and Education Center (ARDEC) in Wellington, CO; USDA ARS Great Plains field research station near Akron, CO (16 year experiment); New Mexico State University Agricultural Science Center near Clovis, NM (4 year experiment);

and Farmer 1 (Casiquito, 7 year experiment) in the Jemez Pueblo, USA. Single-season experiment sites included Farmers 2 (C.Fragua) and 3 (B.Fragua) in the Jemez Pueblo, USA; Farmer 4 (McFarland) near Arriba, CO; and Farmer 5 (Wiltse) near Timken, KS; these producers implemented contrasting practices in subplots of a field that had formerly been managed identically. All of the farmers are co-authors on this paper. The ARDEC, Jemez and Clovis sites had limited irrigation; while the other sites were under dryland management. The field site descriptions and management data are presented in Table 3.1.

3.2.3 Field site treatment and control descriptions

The Akron experiment was established in 2010 to measure the effect of composted feedlot manure and cropping intensity on dryland soil health and crop productivity. Compost was applied to four replicate blocks every 2 years at rates of 23 t ha^{-1} (1X), 109 t ha^{-1} from 2010-2022 and 23 t ha^{-1} thereafter (5X/1X), or no compost. Compost was last applied in summer of 2023. Each plot was divided into four sub-plots, with both phases of two crop rotations (wheat (*Triticum aestivum*) - fallow and wheat - field pea (*Pisum sativum L.*)) across the sub-plots. More information about this site is found in Calderón et al. (2018). I sampled from the wheat - fallow with (trt) and without (ctrl) 5X/1X compost plots from the fallow phase of this study.

The Clovis experiment was established in 2015 to measure the effect of composted feedlot manure and cover crops on soil health and crop productivity. It was a randomized complete block design with eight cover crop treatments and three replicates within each phase of a 3-year wheat (*Triticum aestivum*) - sorghum (*Sorghum bicolor*) -fallow/cover crop rotation. I selected two of the cover crop treatments to use for this study: bare fallow (BF) and a six-species mix (SSM) of pea (*Pisum sativum L.*), oat (*Avena sativa L.*), canola (*Brassica napus L.*), hairy vetch (*Vicia villosa L.*), forage radish (*Raphanus sativus L.*), and barley (*Hordeum vulgare L.*). Since 2022, nested split-plots had compost applied at a rate of 16.8 t ha^{-1}, which was last applied in Feb 2025. More information about this site is found in Ghimire et al. (2019) and Noble Strohm et al. (2025). I sampled two treatment/control pairs from the fallow phase of this study: SSM with (trt) and without (ctrl) compost; BF with (trt) and without (ctrl) compost.

Soils were collected at ARDEC from a field with a long-term history (>50 years) of irrigated conventional tillage and annual cropping (ctrl), and a neighboring field under no-till intermediate wheatgrass (*Thinopyrum intermedium*) since 2014 (trt). The conventional rotation was corn (*Zea mays*)-beans (*Phaseolus vulgaris*)-wheat with an average of 7 tillage passes per cropping season, and received 45 and 18 kg ha^{-1} of N and P respectively one month prior to sampling. The intermediate wheatgrass field was converted from conventional annual cropping in 2014 and received 80 kg ha^{-1} N and weekly irrigation for a cumulative annual application of 260-355mm until 2017, after which it was hayed intermittently and not fertilized. More information about these plots is found in Culman et al. (2013) and Núñez et al. (2022).

Table 3.1: Location, soil, and climatic characteristics of the sites in this study. Soil taxonomic data from Web Soil Survey (Soil Survey Staff et al., 2026), textural data measured in this study. Plot size of the treatment plot is reported with size of the sub- or control plot in parentheses. Climatic data from CEDA (University of East Anglia Climatic Research Unit et al., 2025). Elev = elevation. MAT = mean annual temperature. MAP = mean annual precipitation. pET = mean annual potential evapotranspiration.

Site	Location	Elev.	Taxonomic class	Textural class	Plot size	MAT	MAP	pET	Irrigation	Treatment contrast
		(m)			(m) trt(ctrl)	℃	(mm)	(mm)		trt (ctrl)
ARDEC	40.654, -104.998	1555	Fine-loamy, mixed, superactive, mesic Aridic Haplustalfs	sandy clay loam	85x50 (25x50)	9.2	400	1324	limited	Perennials (conventional annuals)
Akron	40.156, -103.141	1384	Fine, smectitic, mesic [Pachic and Aridic] Argiustolls	silt loam	37x11 (12x11)	10.2	410	1349	dryland	Compost (no compost)
B.Fragua	35.610, -106.749	1696	Coarse-loamy, mixed, superactive, calcareous, mesic Ustic Torriorthents	clay	10x30 (10x30)	8.7	470	1409	limited	Weedy fallow (sorghum covers)
C.Fragua	35.600, -106.736	1691	Mixed, mesic Ustic Torripsamments	loamy sand	4x41 (4x41)	8.7	470	1409	limited	Deep-planted and fertilized corn (traditional)
Casiquito	35.599, -106.738	1693	Fine-silty, mixed, superactive, mesic Ustic Haplocambids	sandy clay loam	11x12 (50x50)	8.7	470	1409	limited	Perennials (conventional annuals)
Clovis	34.601, -103.220	1348	Fine, mixed, thermic Aridic Paleustol	clay loam	18x12 (6x6)	14.7	430	1735	limited	Compost (no compost)
McFarland	39.419, -103.280	1568	Fine-loamy, mixed, superactive, mesic Aridic Argiustolls	sandy loam	31x670 (700x700)	10.1	397	1400	dryland	Vertical tillage (no-till)
Wiltse	38.367, -99.126	631	Fine, smectitic, mesic Typic Argiustolls	silty clay loam	250x250 (17x32)	13.1	638	1479	dryland	Cover crops (bare fallow)

Soils from Casiquito were collected from a field managed with high-diversity field crops (ctrl), and a neighboring orchard field managed with minimal disturbance and annual weedy ground cover (trt). In 2019, the orchard was planted to cherry (*Prunus sp.*), apple (*Malus domestica*), pear (*Pyrus sp.*), peach (*Prunus sp.*), and grape (*Vinifera labrusca*), without amendments. The annual cropping field was planted to diverse crops: corn, chile (*Capsicum annuum var. Jemez Pueblo*), watermelons (*Citrullus lanatus*), native melons (*Cucumis melo*), cucumber (*Cucumis sativus*), onions (*Allium sp.*), and cotton (*Gossypium sp.*), without amendments. Both fields were flood irrigated 1-2x per week.

The Wiltse experiment was set up to measure the effect of no-till cover crops for grazing (trt) compared to dryland no-till bare fallow (ctrl). A single fallow control strip was left unplanted within a field planted in June to a diverse cover crop mix for grazing cattle. Inoculants and 22.4 kg ha^{-1} of extra-slow release N were applied at planting. Cropping history included corn interseeded with cover crops in alternate rows (2024), triticale (× *Triticosecale*) (2022-2023), full-season grazed cover crops (2022), and sorghum (2021). Historically, N rates were well below recommended agronomic rates for each crop (22-39kg ha^{-1} per crop), and weeds were managed with herbicides.

The McFarland experiment was set up to measure the effect of minimum tillage annual cropping (trt) compared to dryland no-till annual cropping (ctrl) to address chemical-resistant annual kochia (*Bassia scoparia*) in long-term no-till soils. An herbicide mix (atrazine, metolachlor, 2,4-D, fluroxypyr, glyphosate, mesotrione) was applied to the majority of the field in June, except for a treatment strip which was instead prepared with tine cultivation and rotary harrowing. Cropping history included sorghum (2024), sunflowers (*Helianthus annuus*) (2023), and wheat (2021-2022). Historically, weeds were managed with herbicides and nitrogen rates were at the rates recommended by the Haney test (approx. 40kg ha^{-1} per crop).

The C.Fragua experiment was set up to measure the effect of planting corn deeply and adding fish-based fertilizer to increase drought tolerance. Conventional tillage practices included hand-tillage with a hoe. Corn was planted in the treatment strip 30cm deep and fertilized with 424 kg ha^{-1} of fish parts, which was the quantity readily available to the farmer. Corn was planted on the control plot 7cm deep using a hoe and no fertilizer was added. The entire field had been taken out of scrubby fallow for this year's experiment, and was flood irrigated weekly.

The B.Fragua experiment was set up to measure the effect of sorghum cover crops compared to an unmanaged weedy fallow, which is cost- and labor-free. The field was planted to sorghum cover crop using a drill with no amendments or fertilizers and flood irrigated 1-2x per week. I sampled soils from subplots dominated by either sorghum (ctrl) or weedy fallow (trt). Annual kochia was the dominant weed in fallowed plots. Cropping history included warm season cover crops (2024) and traditional corn and chile (2023). Historically, amendments including humate and manure were applied every few years.

3.2.4 Substrate decomposition studies

I selected 4 readily available household substrates to use in decomposition assays: two types of tea and two types of cotton. I used green tea leaves (*Camellia sinensis*) and rooibos tea leaves (*Aspalathus linearis*), as well as unbleached cotton fabric (*Gossypium hirsutum*, 7.5x20cm) and unbleached all-natural cotton balls (*Gossypium hirsutum*, 3 per sample). These materials were selected because producers could easily obtain them and they were the materials that showed the most promise by previous researchers (Keuskamp et al., 2013; Middelanis et al., 2023; Middleton et al., 2021).

All laboratory incubations were performed in 1000mL Ball jars in a Fisher Scientific Isotemp incubator. Soils for incubation experiments were sieved to 8mm; roots were retained and cut with scissors to <8mm long. Jars were filled in layers of soil and decomposable substrates (75g soil, substrate, 150g soil, substrate, 75g soil), packing soil to its original bulk density. The volume of the substrate was accounted for and the jars were less than half full. Jars were sealed to prevent water loss and twice per week jars were opened briefly for headspace air recirculation to prevent anaerobic conditions. All samples were incubated at 25℃, based on the average June-Sept soil temperatures at 10 cm deep across three COAgMET weather stations in Eastern Colorado: Burlington South, Lamar #1, and Sand Creek Massacre HS (Colorado Climate Center, 2026).

3.2.4.1 Experiment 1: Methods improvements

I compared decomposition of the original filter bags that the tea came packaged in, compared to 220µm nylon mesh filter bags available from online retailers. Three replicates of empty green, rooibos, and nylon bags, as well as nylon flagging ribbon were incubated at 25℃ and 30% GWC (g H_2O g soil^{-1}) for 120 days. I incubated all 4 substrates in a single jar using alternating layers of ARDEC soil and substrates, for 24 samples in 6 jars (4 substrates x 2 soil treatments x 3 replicates). Substrate order was randomized in each jar.

I evaluated accessible methods for land managers to remove most of the leachable fraction from the substrates. I pre-leached 3 replicates of green tea, rooibos tea, and cotton fabric using room-temperature tap water, and tested 4 durations: 30s under a turbulent running faucet, and soaking in a large bucket for 2 hours, 8 hours, and 24 hours, for 36 samples (4 levels x 3 substrates x 3 replicates). I air-dried them for at least 24 hours. I calculated the percent mass lost from leaching by subtracting the post-leaching substrate mass from the fresh substrate mass, divided by the fresh substrate mass.

I evaluated accessible methods for land managers to remove soil from samples after decomposition, while minimizing the removal of any remaining sample. To roughly test soil contamination removal, I agitated 8-hour pre-leached substrates in a mud slurry and allowed them to air-dry for at least 24 hours, then washed them. To measure the amount of substrate lost during the washing process, I washed pre-leached substrates which had not been muddied. I used 5 methods for washing: a hose running gently (laminar flow) for 2 minutes while the substrate was gently manipulated inside the bag (hose), a washing machine on cold cycle without soap in a lingerie bag (cold machine), a washing machine on hot cycle with standard laundry detergent in a lingerie bag (hot soap), a 20m soak in cold tap water in a large bucket agitated every 5 minutes (tub soak), and spun in a salad spinner with clean water 3 times (salad), for 30 samples (3 replicates x 5 washing levels x 2 mud levels). Contamination remaining was calculated as the mass difference between pre-leached and washed substrate, as a percentage of pre-leached substrate mass.

I validated the effectiveness of removing soil from litterbags using a muffle furnace for ash-correction. I ground and ashed subsamples of incubated, washed substrate at 500℃ for 8 hrs for 64 samples (16 reps x 4 substrate types), as well as 12 fresh, unincubated substrates (3 reps x 4 substrate types). Ash-free dry mass was calculated by subtracting the mass of the remaining ash from the washed mass. I assumed that the mass difference of ash between incubated, washed samples and fresh, unincubated substrates represents the soil contamination remaining in the washed samples.

I evaluated low-cost, consumer-grade weigh scales which are readily available from online retailers (Weigh Gram FN-50 Milligram Scale, 50g/0.001g and Smart Weigh GEM20-20g x 0.001 Grams, High Precision Digital Milligram Jewelry Scale), compared to a laboratory balance (VWR-214B2). Two replicates each of green tea, rooibos tea, and cotton were rebagged into nylon mesh, for 6 samples. One operator weighed them on both scales 5 times each in a randomized order. To compare scale precision, I reported average CV for each scale with all sample pooled. To assess capability of the weigh scale for this purpose, I calculated the relative standard error for each repeatedly-weighed sample.

3.2.4.2 Experiment 2: Sensitivity study

To identify the most responsive substrate to decomposition in paired treatment and control soils, I incubated 2 replicates of pre-leached green tea (EAN 0041000068393), rooibos tea (EAN 0610366407995), cotton fabric (7.5x20cm) and cotton balls at 25℃ for three durations (10 days, 30 days, and 90 days). Soils were oven-dried at 55℃, and during assembly I adjusted each layer of soil to 10% or 30% GWC (high and low soil moisture levels from the COAgMET data above), for 96 samples in 48 jars (4 substrates x 2 soil treatments x 2 moisture levels x 3 durations x 2 replicates). I re-packaged tea in nylon mesh bags and pre-leached all substrates for 8 hours. I incubated two substrates in a single jar using alternating layers of

ARDEC soil and substrate. After incubation, samples were washed using the hose method and air-dried for 24 hours. Percent mass remaining was calculated as:

$$f_{pct} = \frac{m_d}{m_p} * 100 \tag{3.1}$$

where $\mathbf{f_{pct}}$ is the fraction of mass remaining (%), $\mathbf{m_d}$ is the mass of the entire decomposed, washed, and dried substrate package (g), and $\mathbf{m_p}$ is the mass of the entire pre-leached substrate package (g).

3.2.4.3 Experiment 3: Field trial in paired treatment/control plots

One substrate, the green tea, was then tested in a field environment. I repackaged the green tea in nylon bags and pre-leached for 8 hours, and installed bags in the field at all sites except ARDEC. Six replicate pairs were buried at a depth of 5 cm for 31-34 days between July 23 and Aug 8, 2025 except Casiquito which had only 4 replicate pairs due to sample preparation errors. In an effort to expose paired trt/ctrl substrates to the same climatic conditions, I installed pairs within 50 m of each other. A narrow spade was inserted into the soil at an angle, to create a slit into which the teabag was placed, and the soil subsequently closed back up by compressing it gently. In fields with row crops, teabags were buried 10cm from the row. In other fields, tea bags were buried randomly across the plot. In all plots, teabags were not buried within 1m of the plot edge or each other. I lost two trt teabags in the field on B.Fragua as sorghum harvest damaged and buried the flagging ribbons. At retrieval, three teabags had been unearthed and were lying on the soil surface adjacent to where they had been buried (two in Clovis fallow trt and one in Clifford trt), but these were still included in the dataset. After recovery, tea bags were stored in coolers with ice packs during transport to the university laboratory. They were air-dried and weighed, washed using the hose method described above, air-dried, and weighed again. Mass loss was calculated as above.

To estimate climatic conditions during field incubations, I used air temperature data from nearby weather stations: the ZiaMet Weather Station Network (New Mexico Climate Center, 2026) for Jemez and Clovis sites, the Colorado Agricultural Meteorological Network COAgMET (Colorado Climate Center, 2026) for Akron, ARDEC, and McFarland, and Kansas Mesonet (Kansas Mesonet Historical Data, 2026) for Wiltse. I averaged air temperature across the days that the substrates were buried.

Soil sampling and analysis In 2025, I took 0-10cm soil samples at each site concurrent with retrieval of the decomposing substrates. Sampling was done pre-planting at ARDEC (April), during crop growth at Casiquito, Wiltse, McFarland, B.Fragua, and C.Fragua (August), and during the fallow phase at Clovis and

Akron (August). Within each plot, I collected two sets of samples from six randomly chosen sampling points more than 1m away from the edge and avoiding any field anomalies, and composited across replicates.

I collected the first set with a narrow spade to 10cm depth for use in aggregate stability testing and incubation experiments. Soils for aggregate stability testing were sieved to 8mm and air-dried for 7 days. Aggregate stability was estimated using image recognition of soil slaking under fast wetting conditions (Fajardo et al., 2016) using the smartphone application called Slakes, developed by the University of Sydney, Australia. Three pea-sized aggregates were selected and photographed, adjusting the app to capture the actual geometric extent in each photograph. They were transferred to a petri dish full of tap water, and photographed immediately again. After 10 minutes, a third photograph was taken, and an aggregate stability index between 0.1-1 (dimensionless) was calculated to estimate slaking, where 1 represents no change in geometric extent whatsoever.

I collected a second set of soil with a 2.5cm diameter probe to 10cm depth for soil health (Haney) and phospholipid-derived fatty acid (PLFA) at a commercial lab (Regen Ag Lab, LLC, Pleasanton, NE, USA). Soils were kept in coolers with ice packs during transport to the university laboratory; soils for commercial laboratory testing were stored in the freezer at -10℃ and shipped via 2-day shipping in cardboard boxes.

The Haney soil health test was used to obtain several common measures of soil health. In particular, soil organic matter was calculated using loss-on-ignition (% LOI) and soil respiration was evaluated by rewetting soil and incubating for 24 hrs at 24℃ and measuring the carbon dioxide produced (Haney et al., 2018).

PLFA analysis was used to estimate total microbial biomass in the soil. Microbial fatty acids present in the soil were extracted and methylated, and analyzed using gas chromatography. Fatty acid abundance was calculated as nmol g^{-1} of dry soil. The PLFA parameters were described using standard nomenclature, and microbial communities were separated into kingdoms (bacteria and fungi) (White et al., 1979).

Gravimetric water content was measured by weighing a representative field-moist subsample of soil (10g), drying in an oven at 105℃ for at least 48 hours, and reweighing.

3.2.4.4 Experiment 4: Time series incubation with field soils in the laboratory

I designed a second lab incubation to explore the temporal decomposition dynamics of green tea in field-moist soils to identify the most sensitive incubation time (defined as the time point where differences in decomposition were maximized between treatment and control soils). I used soils from the long-term experiment stations and two of the single-season farmer experiments (McFarland and Wiltse). Four replicates of 8-hour pre-leached, re-packaged green tea bags were weighed then incubated at 25℃ for five durations (5, 10, 16, 23, and 31 days). I incubated two samples in each jar for 200 samples in 100 jars (5 sites x 2 treatments x 5 durations x 4 replicates). Soils were kept field-moist and refrigerated at 4℃ until use.

Samples were washed using the hose method and air-dried for 24 hours before being weighed. Mass loss from decomposition was calculated as above.

3.2.5 Data analysis

I conducted all analyses in Python 3.12 (Python Software Foundation, n.d.) using pandas and statsmodels packages, and visualized using matplotlib and seaborn. No data were excluded as outliers. To test for statistical differences between treatment and control teabags in the incubation experiments and SLAKES aggregate stability tests, I performed independent two-sample t-tests at each site with percent mass remaining as the response variable and reported coefficients, standard errors, and p-values for tests significant at the $p<0.05$ level. The t-tests were performed individually for each site because each site was performing a different soil health experiment. I did not analyze results across sites because my goal was to enable producers to measure differences between their own treatment and control soils on their individual operations rather than identifying an indicator that describes general trends across a landscape.

However, I did assess correlations of climatic conditions and laboratory soil health indicators to field study decomposition rates across sites with a correlation matrix and a mixed linear model. I calculated a correlation matrix between decomposition (%, calculated as 100-% mass remaining), aggregate stability (unitless, from SLAKES smartphone app), air temperature (℃), gravimetric soil moisture content (g H_2O g soil^{-1}), sand (%), soil pH, soil organic matter (%), and PLFA total fungi biomass (ng g^{-1} soil). For this analysis, I aggregated data to the site/treatment level since observations were not paired between the decomposition and aggregate stability datasets. I reported the Pearson correlation coefficients and Bonferroni-adjusted p-values. I also fit a mixed linear model with percent mass remaining as the response variable, and predictor variables of treatment (trt vs ctrl), air temperature (℃), gravimetric soil moisture content (g H_2O g soil^{-1}), sand (%), soil pH, soil organic matter (%), and PLFA total fungi biomass (ng g^{-1} soil), blocked with site as a random effect. Indicators were removed from the analysis due to multicollinearity including clay (%), soil respiration (ppm CO_2-C), water-extractable N (ppm N), PLFA total microbial biomass (ng g^{-1} soil), PLFA total bacteria (ng g^{-1} soil), and PLFA saprophytic fungi (ng g^{-1} soil). To evaluate if air temperature from offsite weather stations significantly improved model fit, I performed a likelihood ratio test on the nested linear mixed models fitted using maximum likelihood estimation. I reported the conditional and marginal R^2 of the model as well as estimates, standard errors, and p-values for predictor variables significant at the $p<0.05$ level. For the correlation matrix and the mixed effects model, assumptions of linearity, normality of residuals, and homogeneity of variance were tested.

3.3 Results

3.3.1 Experiment 1: Methods improvements

The original packaging that green and rooibos tea came in decomposed too rapidly to be used in litterbag experiments and nylon bags were a suitable replacement option. After 10 days, off-the-shelf teabag material had decomposed such that the samples were irretrievable. After 120 days, the material was fully decomposed and only trace amounts of the printed tags remained. Nylon mesh bags did not decompose and increased 4% ±1.1% in mass on average, likely due to soil contamination. The nylon flagging ribbon lost an average of 10.3% ±0.3% of its mass over the incubation.

A significant fraction of the substrates was leachable, and green tea had the largest leachable fraction. After 24 hours of soaking, 35.6%, 13.9%, and 6.6% of the original mass was lost for green tea, rooibos tea, and cotton fabric, respectively, Figure 3.1.

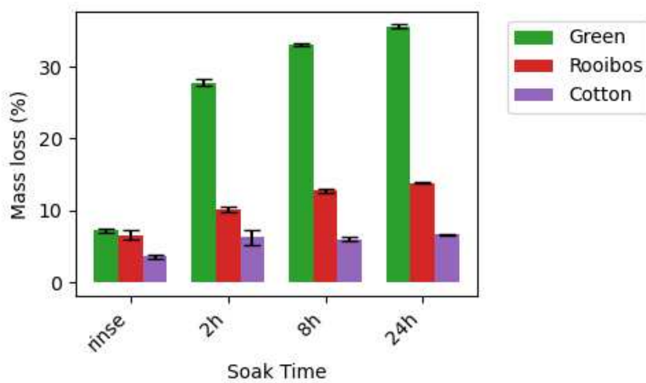

Figure 3.1: Leachable fraction (% mass loss) for three substrates (green or rooibos tea and cotton fabric) after 30 seconds rinsing, or soaking in room-temperature water for 2, 8, or 24 hours. Error bars are standard error. N=3.

There was a wide range of performance from the five washing methods on removing soil while not inducing additional sample loss; the hose method had the best performance on both criteria. After 10- and 30-day incubations, ashing data showed that washing with the hose method showed effectively no soil contamination remaining in the substrate (range of -0.018g to 0.014g). Washing pre-leached, unincubated samples with the hose method caused an additional 0.07g±0.01 of sample to be removed (1.6% of the sample original mass). The salad spinner and tub soak methods left large amounts of soil contamination in the sample (1.2g±0.06 and 1.5g±0.2, respectively). In addition, the cold and hot washing machine methods induced additional sample loss (0.16g±0.007 for the cold cycle without soap and 0.22g±0.01 for hot cycle with soap). All supporting data are available upon request (data not shown).

The consumer-grade scale was less precise than the laboratory balance, but the relative standard error (RSE) for individual samples was very low. The laboratory balance was 4x more precise (CV consumer = 1.67e-3; CV laboratory = 4.06e-4), but relative standard error of individual samples weighed multiple times ranged from 0.06% to 0.12%. All supporting data are available upon request (data not shown).

3.3.2 Experiments #2-4: Incubation experiments

3.3.2.1 Experiment 2: Sensitivity study

Green tea was selected for further study because it had the larger and more consistent mean difference in mass loss between treatment and control soils across moisture levels relative to rooibos tea, cotton fabric, and cotton balls after 30 days in the initial incubation experiment. At 30 days of incubation, mean delta mass loss of green tea (i.e., mass lost in treatment soils subtracted from mass loss in control soils) was 11.3% and 18.9% in high- and low-moisture soils, respectively (Figure 3.2). At 30% moisture level and 90-day decomposition, cotton fabric was the most decomposed out of all the substrates (42.0% remaining). Rooibos tea had the least amount of mass loss of all the substrates at each time point (69.7-100.7% remaining). The control soils (ARDEC annual crops with frequent tillage) tended to have similar or greater mass loss than the treatment soils (ARDEC no-till intermediate wheatgrass) across substrates and time points, but statistical tests were not performed due to low replication (n=2) in this initial study.

3.3.2.2 Experiment 3: Field trial in paired treatment/control plots

In the field study, only two out of eight sites had significant differences in substrate mass loss between treatment and control, with both having more mass loss in the treatment soils: Clovis covers compost vs. no compost (coefficient = -4.5% from ctrl to trt, SE = 1.6, p=0.013) and McFarland min-till vs. no-till (coefficient = -6.4% from ctrl to trt, SE = 2.1, p=0.020). For the remaining sites, the differences were non-significant but mass loss followed the same trend, tending to be greater in trt than ctrl, Figure 3.3.

In a model of percent mass remaining with predictor variables of climatic and soil variables and a random effect for site, none of the predictor variables were significant in explaining the variability in the decomposition data. The marginal R^2 of the full model was 0.048, indicating that the treatment, soil properties, and climate variables explained very little of the variance, while the random effect of location (i.e., conditional R^2) explained 52.9% of the total variance.

There were no relationships between the decomposition data and other laboratory soil health indicators, including pH, organic matter and PLFA total fungi, Figure 3.4. Decomposition was negatively correlated with aggregate stability from the SLAKES app, where increased decomposition was associated with reduced aggregate stability (Pearson's R = -0.76, p = 0.017).

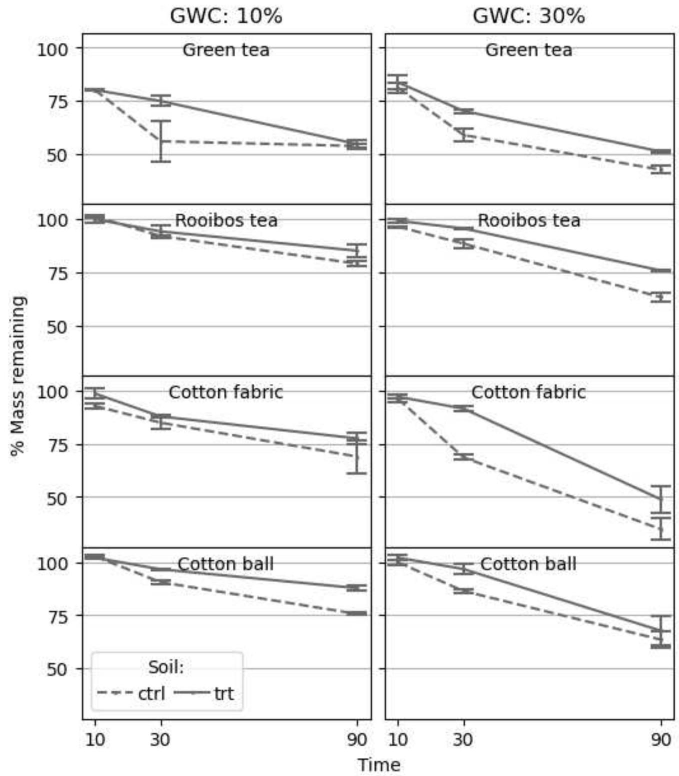

Figure 3.2: Time series of decomposition in ARDEC soils in the laboratory incubator. Control soils were from an irrigated conventional tillage rotation with annual cropping, and treatment soils were from a no-till intermediate wheatgrass rotation. Values represent mean mass remaining (%) in the substrates ±standard error; n=2. Green tea at 30 days had the largest mean difference in mass loss between treatment and control soils. GWC = gravimetric water content (g H_2O g $soil^{-1}$).

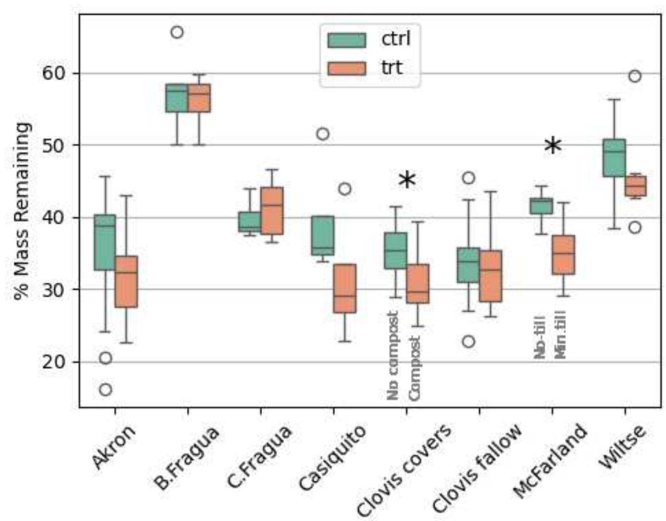

Figure 3.3: Mass remaining (%) after 31-34 day decomposition of green tea in the field, August 2025, n=4-16; asterisks indicate significant differences between substrates buried in trt vs ctrl (*$p < 0.05$). Sample size and treatment/control pairs are: Akron and both Clovis soils, compost/no compost; n=16. B.Fragua, fallow/sorghum root zone soils; n=6. C.Fragua, deep-planted and fertilized/traditional planting; n=6. Casiquito, no-till perennial orchard/annual cropping with tillage; n=4. Wiltse, cover crops/fallow; n=6. McFarland, minimal tillage/no-till; n=6.

Table 3.2: Summary statistics of soil properties and decomposition data across all soils. Mean, standard error, and N are reported for each variable. Soils were sampled from 0-10 cm, with the exception of values for bulk density, which were sampled from 0-5 cm.

Property	Units	n	Mean	SE
Grav. Water Content	g H_2O g soil^{-1}	16	0.2	0.01
Bulk Density	g cm^{-3}	9	1.2	0.02
Sand	%	16	43.9	4.94
Clay	%	16	30.2	2.07
pH	unitless	16	7.8	0.22
Organic Matter	%	16	2.5	0.30
Soil respiration CO_2-C	ppm	16	24.0	3.58
H_2O Total N	ppm	16	32.4	7.02
Microbially active carbon	%	16	16.2	1.09
Soil Health Calculation	unitless	16	6.6	0.89
Total Microbial Biomass	ng g^{-1}	16	2517.6	302.65
Total Bacteria	ng g^{-1}	16	584.5	97.77
Total Fungi	ng g^{-1}	16	158.2	30.04
Saprophytic Fungi	ng g^{-1}	16	83.5	19.49
Protozoa	ng g^{-1}	16	0.6	0.41

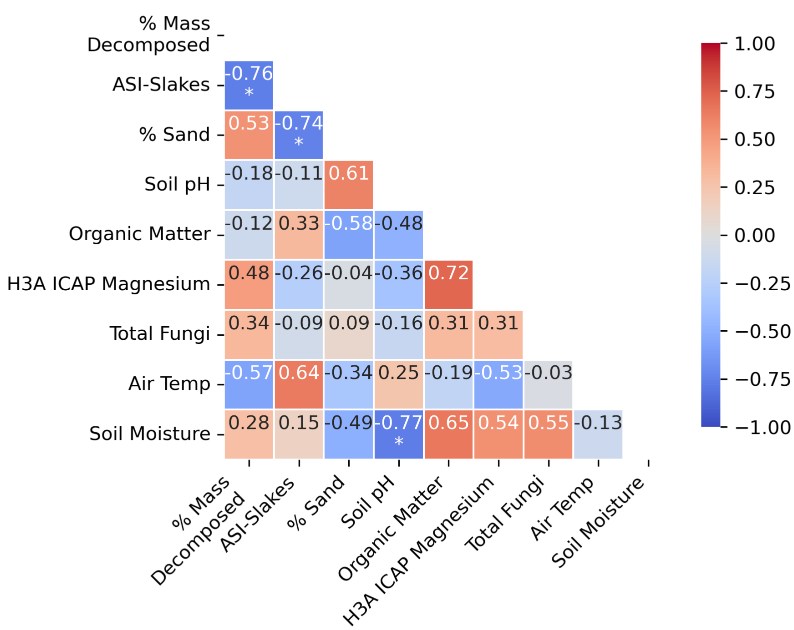

Figure 3.4: Correlogram showing Pearson's correlation coefficients (r) between decomposition (% mass decomposed), laboratory soil indicators and climate variables, n=16. Asterisks indicate significant correlations (Bonferroni-adjusted; *p < 0.05). ASI-Slakes = Aggregate Stability Index from SLAKES smartphone app, unitless; Total Fungi = PLFA Total Fungi, ng g^{-1}; Soil Moisture = Measured GWC g.H20 g.soil^{-1}. To aid interpretation, in this figure decomposition is reported as % Mass Decomposed (1 - % Mass Remaining).

3.3.2.3 Experiment 4: Time series incubation with field soils in the laboratory

Incubating field soils under controlled laboratory conditions did not improve green tea decomposition sensitivity to management for either long-term or single-season management changes, Figure 3.5. Out of 25 measurement points (5 laboratory incubation soils x 5 time points), only 4 (16%) showed differences between treatment and control soils, and each of these was at a unique time point. Akron compost at 16 days reduced decomposition in green tea (coefficient = 10.2% from ctrl to trt, SE = 2.2, p=0.013), but Clovis-covers compost at 5 and 10 days increased decomposition (Clovis-covers at 5 days coefficient = -3.3% from ctrl to trt, SE = 1.1, p=0.026; Clovis-covers at 10 days coefficient = -19.6% from ctrl to trt, SE = 4.4, p=0.0046). Wiltse covers increased decomposition at 23 days (coefficient = -8.8% from ctrl to trt, SE = 2.3, p=0.013). For the remaining sites, the differences were non-significant and there was no general trend of greater mass loss in either trt or ctrl.

3.3.3 Comparison to accessible soil health indicator (SLAKES)

Aggregate stability was not significantly different between treatment and control soils at any site including long-term experiment sites, Figure 3.6. Across sites, the mean aggregate stability index from the SLAKES smartphone app was negatively correlated to green tea decomposition (Pearson's R = -0.76, p = 0.017), Figure 3.7, where greater decomposition was associated with decreased aggregate stability. It was also negatively correlated with sand (Pearson's R = -0.74, p = 0.027), Figure 3.4. These two p-values were Bonferroni-adjusted.

3.4 Discussion

I evaluated whether decomposition of common substrates could be a sensitive soil health indicator, if the existing tea bag index protocols could be adapted to be accessible to producers, and how it compared to an accessible smartphone-based indicator for aggregate stability (SLAKES). This study included a relatively small number of farms (n=8) with diverse management systems and site characteristics. For green tea decomposition, out of 33 measurement points (8 field sites x 1 time point + 5 laboratory incubation soils x 5 time points), only 6 (18%) showed differences between treatment and control soils. Looking only at long-term experiment soils with known differences in soil health, green tea was only able to differentiate treatment contrasts for 4 of 18 (22%) of the measurement points, even though these soils had measurable differences in soil health (Acharya et al., 2019; Adebayo et al., 2025; Noble Strohm et al., 2025). Of the short-term experiments, it is likely that tillage (McFarland) and cover crops (Wiltse) would have led to changes in the soil's capacity to decompose litter, but perhaps not at a level that would be detectable after a single year against a background of high spatial variability. I evaluated varying the decomposition duration and

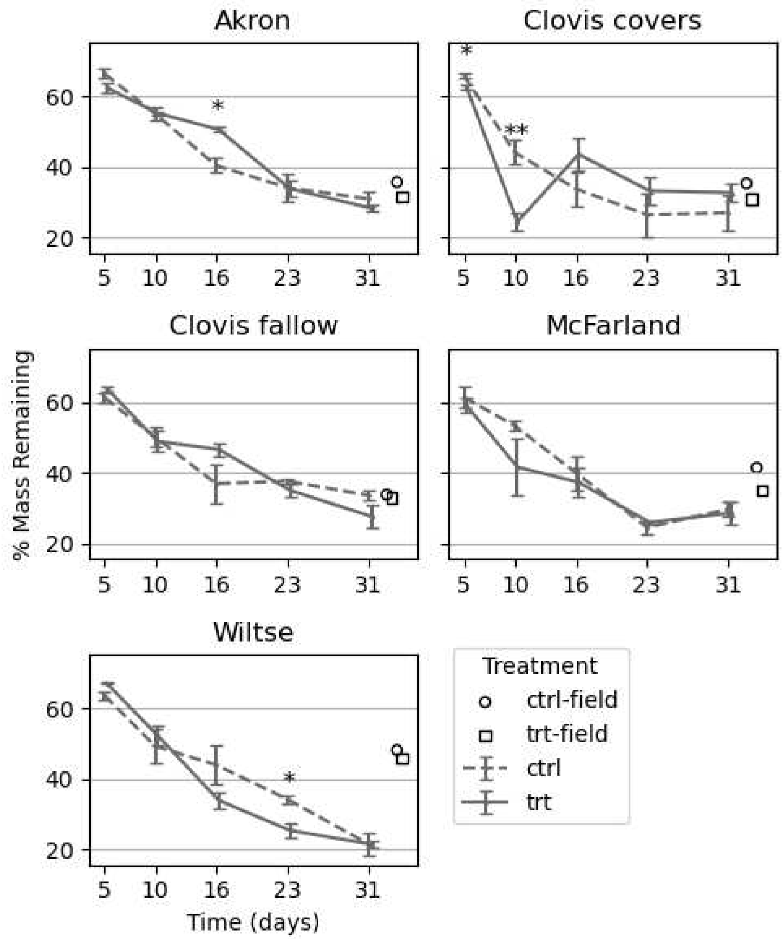

Figure 3.5: Time series of decomposition in field-moist soils in the laboratory incubation study. Values represent mean mass remaining (%) in the substrates ±standard error; n=4. Data from 31-34 day field incubation repeated for reference. Treatment/control pairs are: Akron and both Clovis soils, compost/no compost; B.Fragua, fallow/sorghum root zone soils; C.Fragua, deep-planted and fertilized/traditional planting; Casiquito, no-till perennial orchard/annual cropping with tillage; Wiltse, cover crops/fallow; McFarland, minimal tillage/no-till. Asterisks indicate significant differences between the substrates buried in trt vs ctrl (*p = <0.05, **p<0.01) from t-tests.

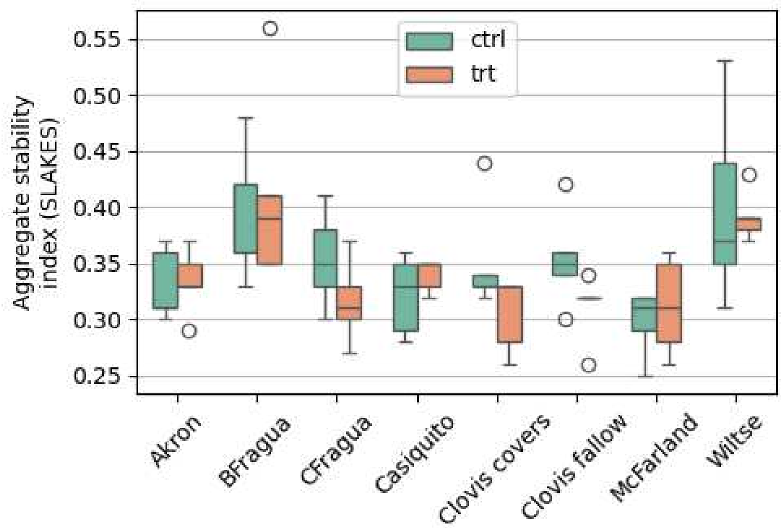

Figure 3.6: Aggregate stability for treatment and control field soils (0-10 cm depth), when measured on air-dried aggregates in the laboratory, n=5. Box plots represent aggregate stability index measured by the SLAKES app (unitless), which has a resolution of 0.1. No treatment/control pair was significant to the p<0.05 level.

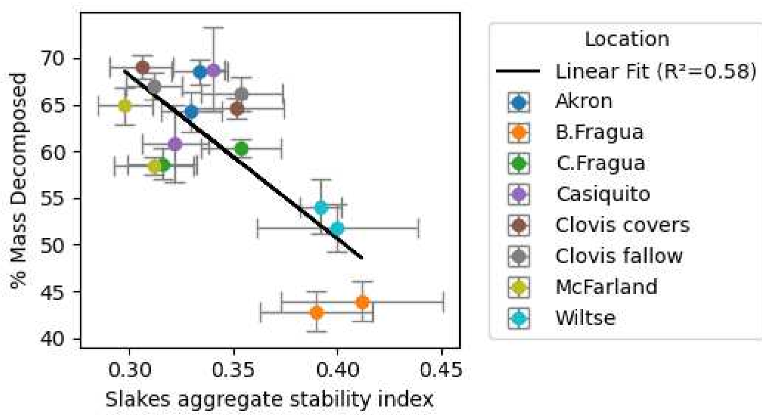

Figure 3.7: Correlation between aggregate stability index (SLAKES smartphone app, unitless) and remaining mass of green tea after decomposition (% mass remaining), n=16. Values on the x-axis represent mean aggregate stability index from air-dried treatment and control soils ±standard error. Values on the y-axis represent mean mass decomposed ±standard error, where % mass decomposed is (100 - % mass remaining).

found that there was no one time point which consistently detected differences between treatment contrasts across sites. In the 30-day field experiment, 2 out of 8 sites showed significant differences in decomposition between treatment and control strips. In the laboratory, 3 sites of 5 had instances of significant differences, but they all occurred at different time points: Clovis covers were different at 5 and 10 days, Akron at 16 days, and Wiltse at 23 days, giving no indication as to the optimal duration of the incubation. For the SLAKES app, no field sites showed differences (0 out of 8). These findings suggest that neither the decomposition of green tea nor aggregate stability as measured by the SLAKES smartphone app are sensitive enough to consistently detect even long-term soil health management changes on individual farms in semi-arid soils. I cannot recommend that producers invest their time to perform either one in treatment/control trials on their own lands.

3.4.1 Tea bag index methods: reducing variability and making it accessible to producers

I was able to adapt the tea bag index methods (Keuskamp et al., 2013) to be more accessible to land managers using their own equipment, by addressing four items: (1) the bagging material, (2) the leachable fraction in green tea, (3) washing to remove soil contamination, and (4) evaluating a consumer-grade weigh scale.

First, the original nylon tetrahedron teabags used by Lipton were discontinued in 2016. Two studies in 2021 showed that the new polypropylene bags were suitable for the 90-day tea bag index protocol (Blume-Werry et al., 2021; Mori et al., 2021). In stark contrast to this, the teabags I purchased in 2025 were far too biodegradable to for an incubation experiment. After 12 days, only 1 out of 18 samples were intact enough to retrieve and weigh (data not shown), and after 120 days, there was near-complete biodegradation and no trace of the tea bag material could be identified within the soil. However, off-the-shelf nylon mesh sleeves are readily available and did not biodegrade under these conditions. Tea leaves can be repackaged into these with minimal extra labor.

Second, I found that the leachable fraction of green tea is significant in comparison to the mass loss I saw during decomposition (35.6% of the mass was leachable, whereas 13% - 84% of the mass decomposed), in agreement with other studies (Blume-Werry et al., 2021; Lind et al., 2022; Mori et al., 2021). The loss of this fraction varies with incubation duration, temperature, and moisture availability in the soil, which overlap with the factors which determine mass loss from mineralization (Lind et al., 2022; Mori et al., 2021; Sarneel et al., 2023). Removing this fraction could reduce variability due to varying moisture conditions (Lind et al., 2022), but Sarneel et al. (2023) argue that it should not be removed prior to incubation experiments. In situ leaching is not synonymous with mass loss because downstream products of leaching are available to microbes for re-stabilization in the substrate. Further, removing this fraction introduces unneeded complexity in an otherwise standardized and simple method. However, I propose that removing the fraction creates a starting mass that is less prone to purely soil moisture-driven losses, and that the added complexity is minimal. Separately, removing this fraction enables the next improvement to the protocol: addressing soil contamination by washing after incubation, rather than ashing in a muffle furnace.

Third, washing is an effective way to remove soil contamination from substrates, on par with ashing in a muffle furnace. While washing methods have been shown to introduce acceptably small amounts of additional leaching in native litters (J. M. Anderson, 1998), the much larger leachable fraction in green tea compared to other litters (Mori et al., 2021) might create unacceptably large losses due to leaching. Pre-leaching the substrates prior to incubation could be an effective way to limit this additional variability. However, washing can also trigger leaching of secondary products of decomposition, which only become leachable after transformation (Sarneel et al., 2023), which may have introduced additional variability into my data. Additionally, the washing method that I found to be the most effective was very time- and water-consuming, requiring substantial time while standing at a running faucet (30 minutes to wash samples from 2 treatments x 6 replicates). I refrained from optimizing this method further after the decomposition data showed the lack of sensitivity to management changes, but the labor required would likely not be feasible for land managers.

Fourth, the consumer-grade scale I used in this study was adequate for this purpose. Relative standard errors of less than 0.12% indicate that very little additional variability would be introduced from using this scale. However, one of the consumer-grade scales did not display the measured mass when it was within 0.020g of a whole number and would instead round to the nearest whole number. Scales should be tested for this feature and avoided.

3.4.2 Evaluate sensitivity to changes in soil health management

In this study, I found that decomposition (measured as mass loss in green tea) was inconsistently able to detect differences between treatment contrasts within the individual long- or short-term soil health experiments. Numerous tea bag studies have been done to evaluate long-term differences in land use or management between sites (e.g., across a chronosequence of sites that adopted no-till practices in Houben et al. (2018)). Results have been mixed from such studies, showing sensitivity (Hayes et al., 2025; Houben et al., 2018; Keuskamp et al., 2013), insensitivity (Djukic et al., 2018; Eggleton et al., 2020; Latterini et al., 2025), or inconsistent sensitivity (Gmach et al., 2024) of decomposition to land use or soil health management changes. While few studies assessed treatment/control contrasts using the tea bag index, my findings aligned with one recent study which found few significant differences between long-term soil health treatment contrasts (M. D. McDaniel et al., 2025; Middleton et al., 2021).

The long-term experiment station soils in this study are known to have differences in some soil health measures. For Akron across both years, Noble Strohm et al. (2025) found differences in bulk density, aggregate stability (mean weight diameter), and bacteria and fungi from ester-linked fatty acid methyl ester (EL-FAME) profiling. At Clovis, they found differences in total microbial and bacterial FAME in one of the two years. Additionally, the addition of compost at Clovis showed effects on soil organic carbon (Acharya et al., 2019) and measures of soil water retention (Adebayo et al., 2025). I hypothesized that these measured differences in soil health properties would be associated with real differences in decomposition capabilities between the treatment contrasts in these sites. However, I found inconsistent directionality of tea bag decomposition between sites. Where Clovis-covers saw more decomposition in compost soils at 5 and 10 days in the laboratory and 30 days in the field, Akron soils saw less decomposition in compost soils at 16 days in the laboratory. Clovis-fallow and all other time points for these three sites saw no differences, and had varying directions. These contrasting results are echoed in the literature, with tea bag decomposition being stimulated (Gmach et al., 2024) or suppressed (M. D. McDaniel et al., 2025) by additions of nitrogen fertilizer, or suppressed by additions of composted horse manure (Duddigan et al., 2022).

It is possible that the experiments testing tillage vs. no-tillage (McFarland) and cover crop vs. fallow (Wiltse) both may have resulted in actual differences in decomposition capabilities, even if these single-season changes were not consistently detectable by this protocol. In the field study, the McFarland site was the only single-season experiment to show differences between treatment contrasts, where tea bags in the tilled plot decomposed more than the ones in the no-till plot. The laboratory incubation did not find any differences in green tea decomposition between tilled and no-till soils, which might be attributable to differences in intact soil structure in the field that were disrupted for the laboratory study. Transitioning to no-till has been shown to have contradictory effects on early-stage litter decomposition, with studies showing positive (Houben et al., 2018), mixed or neutral (Gmach et al., 2024; M. D. McDaniel et al., 2025; Middleton et al., 2021; Wickings et al., 2011), and negative effects (Lupwayi et al., 2004). In the laboratory study, the cover crop experiment at the Wiltse site was the only single-season experiment to show differences between treatment contrasts, where tea bags in the cover crop plot decomposed more than the ones in the fallow plot. This difference was only significant at 23 days, and was not significant in the field. Cover crops and increased cropping diversity have been shown to have stimulating effects on decomposition (Adhikari et al., 2024; M. McDaniel et al., 2014), but one previous tea bag index study did not find significant differences in decomposition between cover crops and fallow treatments (Middleton et al., 2021).

In this study, I found no relationships between the decomposition data and laboratory soil health indicators, including pH, organic matter and PLFA total fungi. In contrast, Middleton et al. (2021) found 4-day green tea decomposition was positively correlated with maize yield, but negatively correlated with the soil health indicators potentially mineralizable C and N, as well as microbial biomass C and N, with some of the relationships being seasonally-dependent. These indicators are connected to pools of carbon and nitrogen in the soil which are strongly linked to microbial activity, so the negative correlation is difficult to interpret. Hayes et al. (2025) found that the remaining mass of green tea had no strong correlations with any of their standard soil analysis measures, including organic matter, texture, or microbial counts.

Climate is assumed to exert major controls on decomposition. Increases in temperature and soil moisture (to a point) can accelerate microbial activity, stimulating decomposition (Gholz et al., 2000; Mori et al., 2021), with some global CO_2 models specifying a doubling of microbial decomposition for every 10 ℃ increase in air temperature (Q10 = 2) (Friedlingstein et al., 2006). A study in agricultural soils in Austria and Sweden found that climatic conditions explained more than 70% of the variation in decomposition rates in green and rooibos tea (Gmach et al., 2024). Even in experiments whose design explicitly attempted to control for climate by using co-located treatment contrasts, Random Forest regression determined that temperature was the overwhelming driver of green tea mass remaining after decomposition (M. D. McDaniel et al., 2025). In that study, temperature was the predictor with the highest importance, accounting for about 40% of the total variance reduction across the model, and was 4x more influential than soil health management (the second most important variable). Controlling for the effects of climate is important to amplify a signal, if it exists, and I attempted to control for climate by installing trt/ctrl pairs within 50 m of each other. Surprisingly, air temperature and soil texture did not explain the variability in decomposition rates between sites. Overall, my model only explained a small proportion of the variance (5%) while random effect of location accounted for most of the variance (53%), suggesting that site-level variables other than soil texture and air temperature were responsible for the variability in the data.

3.4.3 Comparing substrate decomposition with the SLAKES smartphone app

The aggregate stability index measured by the SLAKES smartphone app did not differ between treatment/control pairs within any individual long- or short-term soil health experiments. Several previous studies were able to detect differences between sites with varying land use and soil types, including tillage vs. perennials, cover crops vs. fallow, and forest vs. pasture vs. cropground (Adetsu et al., 2024; Bagnall and Morgan, 2021; Bagnall et al., 2023; Flynn et al., 2020; Jones et al., 2021). However, instead of detecting differences between sites, I wanted to use this method to distinguish between treatments within a site, to enable producers to evaluate the results of their experiments; the literature is less promising for using SLAKES in that way. Using the data from the North American Project to Evaluate Soil Health Measurements, Rieke et al. (2022) found that among the 4 aggregate stability methods tested, SLAKES had the largest percent variance attributable to site (77%), with among-treatment accounting for 12% and 11% within-treatment. Studies that reported treatment contrasts within sites found that SLAKES was unable to detect management effects, including the effects of biochar, crop type, compost applications, and cover crops (Obour et al., 2023; Yost et al., 2024). Yost et al. (2024) suspected that 2 replications of SLAKES testing per treatment was insufficient to detect differences, which is supported by the analysis in Fajardo et al. (2025) which found that reproducible results are obtained after approximately 15 measurements. Five replicates was insufficient to detect differences in this study, and even that might be unrealistic from a labor standpoint.

Previous studies found that the SLAKES aggregate stability test correlated with laboratory indicators. Correlations of increased aggregate stability were found with increasing organic carbon (Bagnall and Morgan, 2021; Fajardo et al., 2016; Jones et al., 2021; Obour et al., 2023; Rieke et al., 2022), but I did not find a relationship with organic matter across these sites. Where previous studies found relationships with texture, increasing SLAKES aggregate stability was associated with increasing sand or decreasing clay (Jones et al., 2021; Rieke et al., 2022). Rieke et al. (2022) attributed this to the SLAKES image-recognition methods: dispersing sand particles won't drift as far from the original aggregate as dispersing clay particles, resulting in smaller final footprints captured in a photograph. In contrast, I saw a significant negative correlation between aggregate stability and soil sand content, and this finding is well-supported in the literature (Bouyoucos, 1935; Levy and Miller, 1997).

This is the first study to my knowledge to compare these two accessible soil health protocols (SLAKES and the tea bag index), and I found a significant negative correlation between the indicators (Pearson's R = -0.76, Bonferroni-adjusted p = 0.017). It has generally been well-established that additions of organic matter to the soil triggers microbially-mediated soil particle stabilization into organo-mineral complexes, including the release of soil-binding molecules such as lipids and polysaccharides and the growth of fungal hyphae (Tisdall and Oades, 1982). In this study, increased decomposition was associated with decreased aggregate stability, which does not align with this conceptual understanding. Significant negative correlations were found between green tea decomposition and biological soil health metrics in a previous study (Middleton et al., 2021), which together cast doubts on the assumption that greater mass loss from decomposition is associated with elevated microbial activity.

3.4.4 A soil health indicator to empower land managers

The aim of the present study was to seek a sensitive and reliable indicator that could be used by a single producer, on a single field, to inform their own experimentation and their annual investment in soil health practices. Developing and assessing soil health indicators is an active area of soil science, and consensus has not yet been reached (Bagnall et al., 2023; Chang et al., 2022; Fierer et al., 2021). Indicators of soil health are considered to be 'useful' if they are (1) responsive to real-time changes in management (Bagnall et al., 2023; Doran, 2002; Hayes et al., 2025) but without high variability dominated by stochastic effects (Doran and Zeiss, 2000; Fierer et al., 2021), (2) are measuring functions that are relevant to the users of the data (Hayes et al., 2025; Janzen et al., 2021), and (3) are accessible to users (cost, time, and interpretability of the results) (Fierer et al., 2021). Further, (4) their findings should be consistent among varying climates, site characteristics, and land uses (Bagnall et al., 2023). If an indicator reports both increased and decreased responses for the same practice between sites, then it is not useful for determining if practices lead to increased functioning of soils; further work might be needed to understand what mediates those contrasting responses.

In this study, I assessed the tea bag index and SLAKES smartphone app for these attributes. The tea bag index and SLAKES app both measure functions relevant to users, namely aggregate stability and microbial decomposition (item 2, above), and are accessible to users (item 3). However, the tea bag index data in this study was rarely responsive to either short- or long-term changes in management, with sometimes contradictory responses (items 1 and 4). The SLAKES app was not responsive to changes in management in this study, including long-term experiment soils (item 1).

Possibly the best indicator is a multidisciplinary collection of indicators, aggregated into a single index, drawing data from across multiple soil functions working together (Bastida et al., 2008). These attributes combine to make an indicator of soil health whose data could be used to make management decisions about the land in question. The tea bag index, in particular, was promising because it is not a point-in-time measurement of isolated characteristics, but instead integrates the effects of dynamic microbial processes and soil properties over a period of time. Further, it directly measures a function of interest in soils (decomposition). I had hoped that this could capture interconnected properties of soil health and quantify functional capabilities for decomposition.

3.5 Conclusion

Land managers are making soil health decisions every year, which collectively determine how many hectares of agricultural land are under soil health management across the globe, and they currently have no quantitative tools sensitive enough to help guide these annual decisions. Soils change slowly and are highly variable in space and time, with detectable change rates of up to a decade in semi-arid soils for some foundational attributes of soil health such as carbon content (Fierer et al., 2021; Lal, 2004). Perhaps an indicator this sensitive and repeatable is impossible to achieve; maybe there will not be true differences in decomposition or aggregate stability in paired soils such as the ones in this study. However, even in long-term experiments with known differences in soil health, I only detected differences in green tea decomposition for 22% of the treatment contrasts, and there were contrasting results for whether compost stimulated or suppressed decomposition. The SLAKES app was unable to detect any differences between the treatment contrasts in this study. Both methods lacked the sensitivity to changes in management and reliability of results that producers need to evaluate the impacts of their soil health experiments. There remains a need to test accessible tools for their capability as single-season, field-specific soil health indicators for semi-arid soils. Such an indicator would be a boon to land managers in the High Plains region, giving them the quantitative data they need to navigate the thousands of decisions that must be made in order to successfully implement soil health practices on their operations.

Bibliography

Acharya, P., Ghimire, R., & Cho, Y. (2019). Linking soil health to sustainable crop production: Dairy compost effects on soil properties and sorghum biomass. *Sustainability*, *11*(13), 3552. https://doi.org/10.3390/su11133552

Adebayo, O., Singh, A., Bista, P., Angadi, S., & Ghimire, R. (2025). Compost addition improves soil water storage and crop water productivity in cover crop integrated sorghum production system under a limited irrigation management. *Irrigation Science*, *43*(6), 1559–1573. https://doi.org/10.1007/s00271-025-01011-2

Adetsu, D. V., Arthur, E., Fu, Y., Cornelis, W., & Lamandé, M. (2024). Exploratory assessment of the SLAKES method to characterize aggregate stability across diverse soil types. *Soil Science Society of America Journal*, *88*(4), 1086–1099. https://doi.org/10.1002/saj2.20674

Adhikari, A. D., Shrestha, P., Ghimire, R., Liu, Z., Pollock, D. A., Acharya, P., & Aryal, D. R. (2024). Cover crop residue quality regulates litter decomposition dynamics and soil carbon mineralization kinetics in semi-arid cropping systems. *Applied Soil Ecology*, *193*, 105160. https://doi.org/10.1016/j.apsoil.2023.105160

Agroecology Summit 'Outside Empire' Subgroup. (2024). A declaration of commitments toward agroecology pluralities: A critical gaze on the u.s. agroecology summit 2023. *Journal of Agriculture, Food Systems, and Community Development*, 1–14. https://doi.org/10.5304/jafscd.2024.133.013

Altieri, M. A., & Rosset, P. (1996). Agroecology and the conversion of lárge-scale conventional systems to sustainable management. *International Journal of Environmental Studies*, *50*(3), 165–185. https://doi.org/10.1080/00207239608711055

Anderson, C. R., Maughan, C., & Pimbert, M. P. (2019). Transformative agroecology learning in europe: Building consciousness, skills and collective capacity for food sovereignty. *Agriculture and Human Values*, *36*(3), 531–547. https://doi.org/10.1007/s10460-018-9894-0

Anderson, J. M. (Ed.). (1998). *Tropical soil biology and fertility: A handbook of methods* (2. ed., repr). CABI Publ.

Asprooth, L., Norton, M., & Galt, R. (2023). The adoption of conservation practices in the corn belt: The role of one formal farmer network, practical farmers of iowa. *Agriculture and Human Values*, *40*(4), 1559–1580. https://doi.org/10.1007/s10460-023-10451-5

Aune, J. B. (2012). Conventional, organic and conservation agriculture: Production and environmental impact. In E. Lichtfouse (Ed.), *Agroecology and strategies for climate change* (pp. 149–165). Springer Netherlands. https://doi.org/10.1007/978-94-007-1905-7_7

Bagnall, D. K., McIntosh, W. A., Morgan, C. L., Woodward, R. T., Cisneros, M., Black, M., Kiella, E. M., & Ale, S. (2020). Farmers' insights on soil health indicators and adoption. *Agrosystems, Geosciences & Environment*, *3*(1), e20066. https://doi.org/10.1002/agg2.20066

Bagnall, D. K., & Morgan, C. L. (2021). SLAKES and 3d scans characterize management effects on soil structure in farm fields. *Soil and Tillage Research*, *208*, 104893. https://doi.org/10.1016/j.still.2020.104893

Bagnall, D. K., Rieke, E. L., Morgan, C. L. S., Liptzin, D. L., Cappellazzi, S. B., & Honeycutt, C. W. (2023). A minimum suite of soil health indicators for north american agriculture. *Soil Security*, *10*, 100084. https://doi.org/10.1016/j.soisec.2023.100084

Barel, J. M., Kuyper, T. W., Paul, J., De Boer, W., Cornelissen, J. H. C., & De Deyn, G. B. (2019). Winter cover crop legacy effects on litter decomposition act through litter quality and microbial community changes (L. Cheng, Ed.). *Journal of Applied Ecology*, *56*(1), 132–143. https://doi.org/10.1111/1365-2664.13261

Bastida, F., Zsolnay, A., Hernández, T., & García, C. (2008). Past, present and future of soil quality indices: A biological perspective. *Geoderma*, *147*(3), 159–171. https://doi.org/10.1016/j.geoderma.2008.08.007

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

Blesh, J., & Schipanski, M. (2024). Blending knowledge systems for agroecological nutrient management and climate resilience. *Journal of Agriculture, Food Systems, and Community Development*, 1–5. https://doi.org/10.5304/jafscd.2024.133.004

Blume-Werry, G., Di Maurizio, V., Beil, I., Lett, S., Schwieger, S., & Kreyling, J. (2021). Don't drink it, bury it: Comparing decomposition rates with the tea bag index is possible without prior leaching. *Plant and Soil*, *465*(1), 613–621. https://doi.org/10.1007/s11104-021-04968-z

Bogel, C. (n.d.). *QualCoder* (Version 3.7). Open Source. Retrieved May 1, 2026, from https://qualcoder.org/

Borer, B., Tecon, R., & Or, D. (2018). Spatial organization of bacterial populations in response to oxygen and carbon counter-gradients in pore networks. *Nature Communications*, *9*(1), 769. https://doi.org/10.1038/s41467-018-03187-y

Bouyoucos, G. J. (1935). The clay ratio as a criterion of susceptibility of soils to erosion[1]. *Agronomy Journal*, *27*(9), 738–741. https://doi.org/10.2134/agronj1935.00021962002700090007x

Brown, G. (2018). *Dirt to soil: One family's journey into regenerative agriculture*. Chelsea Green Publishing.

Bruyn, L. A. L. D., & Abbey, J. A. (2003). Characterisation of farmers' soil sense and the implications for on-farm monitoring of soil health. *Australian Journal of Experimental Agriculture*, *43*(3), 285. https://doi.org/10.1071/EA00176

Bullock, D. S., Boerngen, M., Tao, H., Maxwell, B., Luck, J. D., Shiratsuchi, L., Puntel, L., & Martin, N. F. (2019). The data-intensive farm management project: Changing agronomic research through on-farm precision experimentation. *Agronomy Journal*, *111*(6), 2736–2746. https://doi.org/10.2134/agronj2019.03.0165

Calderón, F. J., Vigil, M. F., & Benjamin, J. (2018). Compost input effect on dryland wheat and forage yields and soil quality. *Pedosphere*, *28*(3), 451–462. https://doi.org/10.1016/S1002-0160(17)60368-0

Carlisle, L. (2016). Factors influencing farmer adoption of soil health practices in the united states: A narrative review. *Agroecology and Sustainable Food Systems*, *40*(6), 583–613. https://doi.org/10.1080/21683565.2016.1156596

Carolan, M. S. (2005). Barriers to the adoption of sustainable agriculture on rented land: An examination of contesting social fields*. *Rural Sociology*, *70*(3), 387–413. https://doi.org/10.1526/0036011054831233

Chang, T., Feng, G., Paul, V., Adeli, A., & Brooks, J. P. (2022). Soil health assessment methods: Progress, applications and comparison. In *Advances in agronomy* (pp. 129–210, Vol. 172). Elsevier. https://doi.org/10.1016/bs.agron.2021.10.002

Colorado Climate Center. (2026). COAgMET: The colorado agricultural meteorological network. Retrieved January 26, 2026, from https://coagmet.colostate.edu/

Conant, R. T., Ogle, S. M., Paul, E. A., & Paustian, K. (2011). Measuring and monitoring soil organic carbon stocks in agricultural lands for climate mitigation. *Frontiers in Ecology and the Environment*, *9*(3), 169–173. https://doi.org/10.1890/090153

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 *Advances in agronomy* (pp. 1–66, Vol. 172). Elsevier. https://doi.org/10.1016/bs.agron.2021.11.002

Culman, S. W., Snapp, S. S., Green, J. M., & Gentry, L. E. (2013). Short- and long-term labile soil carbon and nitrogen dynamics reflect management and predict corn agronomic performance. *Agronomy Journal*, *105*(2), 493–502. https://doi.org/10.2134/agronj2012.0382

Daniel, P. (2013). *Dispossession: Discrimination against african american farmers in the age of civil rights* [done]. University of North Carolina Press.

Deci, E., & Flaste, R. (1995). *Why we do what we do*. Grosset/Putnam.

Djukic, I., Kepfer-Rojas, S., Schmidt, I. K., Larsen, K. S., Beier, C., Berg, B., Verheyen, K., Caliman, A., Paquette, A., Gutiérrez-Girón, A., Humber, A., Valdecantos, A., Petraglia, A., Alexander, H., Augustaitis, A., Saillard, A., Fernández, A. C. R., Sousa, A. I., Lillebø, A. I., . . . Tóth, Z. (2018). Early stage litter decomposition across biomes. *Science of The Total Environment*, *628-629*, 1369–1394. https://doi.org/10.1016/j.scitotenv.2018.01.012

Doran, J. W. (2002). Soil health and global sustainability: Translating science into practice. *Agriculture, Ecosystems & Environment*, *88*(2), 119–127. https://doi.org/10.1016/S0167-8809(01)00246-8

Doran, J. W., & Zeiss, M. R. (2000). Soil health and sustainability: Managing the biotic component of soil quality. *Applied Soil Ecology*, *15*(1), 3–11. https://doi.org/10.1016/S0929-1393(00)00067-6

Duddigan, S., Alexander, P. D., Shaw, L. J., Sandén, T., & Collins, C. D. (2020). The tea bag index—UK: Using citizen/community science to investigate organic matter decomposition rates in domestic gardens. *Sustainability*, *12*(17), 6895. https://doi.org/10.3390/su12176895

Duddigan, S., Shaw, L. J., Alexander, P. D., & Collins, C. D. (2020). Chemical underpinning of the tea bag index: An examination of the decomposition of tea leaves. *Applied and Environmental Soil Science*, *2020*, 1–8. https://doi.org/10.1155/2020/6085180

Duddigan, S., Shaw, L. J., Alexander, P. D., & Collins, C. D. (2022). Effects of application of horticultural soil amendments on decomposition, quantity, stabilisation and quality of soil carbon. *Scientific Reports*, *12*(1), 17631. https://doi.org/10.1038/s41598-022-22451-2

Dunbar-Ortiz, R. (1980). *Roots of resistance: Land tenure in new mexico, 1680-1980*. Chicano Studies Research Center Publications, University of California, Los Angeles : American Indian Studies Center, University of California, Los Angeles.

Ebitu, L., Avery, H., Mourad, K. A., & Enyetu, J. (2021). Citizen science for sustainable agriculture – a systematic literature review. *Land Use Policy*, *103*, 105326. https://doi.org/10.1016/j.landusepol.2021.105326

Edwards, R., & Friefeld, J. K. (2023). *The first migrants: How black homesteaders' quest for land and freedom heralded america's great migration* [done written]. University of Nebraska Press. Retrieved February 24, 2024, from https://www.jstor.org/stable/jj.5076332

Eggleton, P., Griffiths, H., Ashton, L., Law, S., Evans, T., & Parr, K. (2020, November 10). Not our cup of tea: The tea bag index (kueskamp et al. 2013) for assessing decomposition is problematic in most environments, due to macrofauna. https://doi.org/10.22541/au.160502884.44867586/v1

Ellis, E. C., Pascual, U., & Mertz, O. (2019). Ecosystem services and nature's contribution to people: Negotiating diverse values and trade-offs in land systems. *Current Opinion in Environmental Sustainability*, *38*, 86–94. https://doi.org/10.1016/j.cosust.2019.05.001

Fajardo, M., McBratney, A. B., Field, D. J., & Minasny, B. (2016). Soil slaking assessment using image recognition. *Soil and Tillage Research*, *163*, 119–129. https://doi.org/10.1016/j.still.2016.05.018

Fajardo, M., Pino, V., Jones, E., Morgan, C., Stevenson, B., Saby, N., Lacoste, M., & McBratney, A. (2025). Measuring soil aggregate stability with mobile phones, lessons, challenges, and future work. *Scientific Reports*, *15*(1), 24536. https://doi.org/10.1038/s41598-025-09925-9

Fierer, N. (2017). Embracing the unknown: Disentangling the complexities of the soil microbiome. *Nature Reviews Microbiology*, *15*(10), 579–590. https://doi.org/10.1038/nrmicro.2017.87

Fierer, N., Wood, S. A., & Bueno de Mesquita, C. P. (2021). How microbes can, and cannot, be used to assess soil health. *Soil Biology and Biochemistry*, *153*, 108111. https://doi.org/10.1016/j.soilbio.2020.108111

Fleckenstein, M., Lythgoe, A., Lu, J., Thompson, N., Doering, O., Harden, S., Getson, J. M., & Prokopy, L. (2020). Crop insurance: A barrier to conservation adoption? *Journal of Environmental Management*, *276*, 111223. https://doi.org/10.1016/j.jenvman.2020.111223

Flynn, K. D., Bagnall, D. K., & Morgan, C. L. (2020). Evaluation of SLAKES, a smartphone application for quantifying aggregate stability, in high-clay soils. *Soil Science Society of America Journal*, *84*(2), 345–353. https://doi.org/10.1002/saj2.20012

Francis, D. V., Hamilton, D., Mitchell, T. W., Rosenberg, N. A., & Stucki, B. W. (2022). Black land loss: 1920–1997. *AEA Papers and Proceedings*, *112*, 38–42. https://doi.org/10.1257/pandp.20221015

Frankel-Goldwater, L., Wojtynia, N., & Dueñas-Ocampo, S. (2024). Healthy people, soils, and ecosystems: Uncovering primary drivers in the adoption of regenerative agriculture by US farmers and ranchers. *Frontiers in Sustainable Food Systems*, *7*, 1070518. https://doi.org/10.3389/fsufs.2023.1070518

Franzluebbers, A. J., Wright, S. F., & Stuedemann, J. A. (2000). Soil aggregation and glomalin under pastures in the southern piedmont USA. *Soil Science Society of America Journal*, *64*(3), 1018–1026. https://doi.org/10.2136/sssaj2000.6431018x

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., Von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H. D., . . . Zeng, N. (2006). Climate–carbon cycle feedback analysis: Results from the c4mip model intercomparison. *Journal of Climate*, *19*(14), 3337–3353. https://doi.org/10.1175/JCLI3800.1

Friedrichsen, C. N., Hagen-Zakarison, S., Friesen, M. L., McFarland, C. R., Tao, H., & Wulfhorst, J. (2021). Soil health and well-being: Redefining soil health based upon a plurality of values. *Soil Security*, *2*, 100004. https://doi.org/10.1016/j.soisec.2021.100004

Gallardo, R. K. (2024). The environmental impacts of agriculture: A review. *International Review of Environmental and Resource Economics*, *18*(1), 165–235. https://doi.org/10.1561/101.00000166

Ghimire, R., Ghimire, B., Mesbah, A. O., Sainju, U. M., & Idowu, O. J. (2019). Soil health response of cover crops in winter wheat–fallow system. *Agronomy Journal*, *111*(4), 2108–2115. https://doi.org/10.2134/agronj2018.08.0492

Gholz, H. L., Wedin, D. A., Smitherman, S. M., Harmon, M. E., & Parton, W. J. (2000). Long-term dynamics of pine and hardwood litter in contrasting environments: Toward a global model of decomposition. *Global Change Biology*, *6*(7), 751–765. https://doi.org/10.1046/j.1365-2486.2000.00349.x

Gmach, M. R., Bolinder, M. A., Menichetti, L., Kätterer, T., Spiegel, H., Åkesson, O., Friedel, J. K., Surböck, A., Schweinzer, A., & Sandén, T. (2024). Evaluating the tea bag index approach for different management practices in agroecosystems using long-term field experiments in austria and sweden. *SOIL*, *10*(1), 407–423. https://doi.org/10.5194/soil-10-407-2024

Gomiero, T., Giampietro, M., & Mayumi, K. (2006). Facing complexity on agro-ecosystems: A new approach to farming system analysis. *International Journal of Agricultural Resources, Governance and Ecology*, *5*(2), 116. https://doi.org/10.1504/IJARGE.2006.009160

Gordon, E., Davila, F., & Riedy, C. (2022). Transforming landscapes and mindscapes through regenerative agriculture. *Agriculture and Human Values*, *39*(2), 809–826. https://doi.org/10.1007/s10460-021-10276-0

Haney, R. L., Haney, E. B., Smith, D. R., Harmel, R. D., & White, M. J. (2018). The soil health tool—theory and initial broad-scale application. *Applied Soil Ecology*, *125*, 162–168. https://doi.org/10.1016/j.apsoil.2017.07.035

Hansen, N. C., Allen, B. L., Baumhardt, R. L., & Lyon, D. J. (2012). Research achievements and adoption of no-till, dryland cropping in the semi-arid u.s. great plains. *Field Crops Research*, *132*, 196–203. https://doi.org/10.1016/j.fcr.2012.02.021

Hansson, S. O. (2019). Farmers' experiments and scientific methodology. *European Journal for Philosophy of Science*, *9*(3), 32. https://doi.org/10.1007/s13194-019-0255-7

Hartmann, M., & Six, J. (2023). Soil structure and microbiome functions in agroecosystems. *Nature Reviews Earth & Environment*, *4*(1), 4–18. https://doi.org/10.1038/s43017-022-00366-w

Hayes, E. B., Norris, C. E., & Volpe, J. P. (2025). Assessment of teabag litter decomposition as a measure of soil health, including sensitivity to crop type and management system in agricultural soils. *Soil Use and Management*, *41*(2), e70095. https://doi.org/10.1111/sum.70095

Herrick, J. (1995). Simple method for determination of mass loss rates for soil-contaminated samples in decomposition studies. *Pedobiologia*, *39*(1), 74–77. https://doi.org/10.1016/S0031-4056(24)00165-3

Hochmuth, G., Mylavarapu, R., & Hanlon, E. (2014). Soil testing for plant-available nutrients—what is it and why do we use it?: SL408/SS621, 10/2014. *EDIS*, *2014*(8). https://doi.org/10.32473/edis-ss621-2014

Honeycutt, C. W., Morgan, C. L., Elias, P., Doane, M., Mesko, J., Myers, R., Odom, L., Moebius-Clune, B., & Nichols, R. (2020). Soil health: Model programs in the USA. *Frontiers of Agricultural Science and Engineering*, *7*(3), 356. https://doi.org/10.15302/J-FASE-2020340

Houben, D., Faucon, M.-P., & Mercadal, A.-M. (2018). Response of organic matter decomposition to no-tillage adoption evaluated by the tea bag technique. *Soil Systems*, *2*(3), 42. https://doi.org/10.3390/soilsystems2030042

Idol, T. W., Holzbaur, K. A., Pope, P. E., & Ponder, F. (2002). Control-bag correction for forest floor litterbag contamination. *Soil Science Society of America Journal*, *66*(2), 620–623. https://doi.org/10.2136/sssaj2002.6200

Jackson-Smith, D., Ewing, S., Jones, C., Sigler, A., & Armstrong, A. (2018). The road less traveled: Assessing the impacts of farmer and stakeholder participation in groundwater nitrate pollution research. *Journal of Soil and Water Conservation*, *73*(6), 610–622. https://doi.org/10.2489/jswc.73.6.610

Jamiołkowska, A., Księżniak, A., Gałązka, A., Hetman, B., Kopacki, M., & Skwaryło-Bednarz, B. (2018). Impact of abiotic factors on development of the community of arbuscular mycorrhizal fungi in the soil: A review. *International Agrophysics*, *32*(1), 133–140. https://doi.org/10.1515/intag-2016-0090

Jandl, R., Rodeghiero, M., Martinez, C., Cotrufo, M. F., Bampa, F., Van Wesemael, B., Harrison, R. B., Guerrini, I. A., Richter, D. d., Rustad, L., Lorenz, K., Chabbi, A., & Miglietta, F. (2014). Current status, uncertainty and future needs in soil organic carbon monitoring. *Science of The Total Environment*, *468-469*, 376–383. https://doi.org/10.1016/j.scitotenv.2013.08.026

Janzen, H. H., Janzen, D. W., & Gregorich, E. G. (2021). The ‘soil health’ metaphor: Illuminating or illusory? *Soil Biology and Biochemistry*, *159*, 108167. https://doi.org/10.1016/j.soilbio.2021.108167

Jenkins, M. E. (1972). Spanish land grants in the tewa area. *New Mexico Historical Review*, *47*(2). https://digitalrepository.unm.edu/nmhr/vol47/iss2/3

Jones, E. J., Filippi, P., Wittig, R., Fajardo, M., Pino, V., & McBratney, A. B. (2021). Mapping soil slaking index and assessing the impact of management in a mixed agricultural landscape. *SOIL*, *7*(1), 33–46. https://doi.org/10.5194/soil-7-33-2021

Jordan, M. (2021). Black US farmers dismayed as white farmers' lawsuit halts relief payments. *The Guardian*. Retrieved March 25, 2024, from https://www.theguardian.com/us-news/2021/jun/22/black-farmers-loan-payments

Kansas Mesonet Historical Data. (2026). Kansas mesonet, 2026. Retrieved January 26, 2026, from http://mesonet.k-state.edu/weather/historical

Kelly, C., Schipanski, M. E., Tucker, A., Trujillo, W., Holman, J. D., Obour, A. K., Johnson, S., Brummer, J. E., Haag, L., & Fonte, S. J. (2021). Dryland cover crop soil health benefits are maintained with grazing in the u.s. high and central plains. *Agriculture, Ecosystems & Environment*, *313*, 107358. https://doi.org/10.1016/j.agee.2021.107358

Keuskamp, J. A., Dingemans, B. J. J., Lehtinen, T., Sarneel, J. M., & Hefting, M. M. (2013). Tea bag index: A novel approach to collect uniform decomposition data across ecosystems (H. Muller-Landau, Ed.). *Methods in Ecology and Evolution*, *4*(11), 1070–1075. https://doi.org/10.1111/2041-210X.12097

Klein, A. O., Carlisle, L., Lloyd, M. G., Sayre, N. F., & Bowles, T. M. (2024). Understanding farmer knowledge of soil and soil management: A case study of 13 organic farms in an agricultural landscape of northern california. *Agroecology and Sustainable Food Systems*, *48*(1), 17–49. https://doi.org/10.1080/21683565.2023.2270451

Lacoste, M., Cook, S., McNee, M., Gale, D., Ingram, J., Bellon-Maurel, V., MacMillan, T., Sylvester-Bradley, R., Kindred, D., Bramley, R., Tremblay, N., Longchamps, L., Thompson, L., Ruiz, J., García, F. O., Maxwell, B., Griffin, T., Oberthür, T., Huyghe, C., ... Hall, A. (2021). On-farm experimentation to transform global agriculture. *Nature Food*, *3*(1), 11–18. https://doi.org/10.1038/s43016-021-00424-4

Lal, R. (2004). Carbon sequestration in dryland ecosystems. *Environmental Management*, *33*(4). https://doi.org/10.1007/s00267-003-9110-9

Lash, S., Szerszynski, B., & Wynne, B. (1998). *Risk, environment and modernity: Towards a new ecology* [sociology]. SAGE Publications Ltd. Retrieved September 19, 2024, from https://sk.sagepub.com/books/risk-environment-and-modernity

Latterini, F., Horodecki, P., Dyderski, M. K., Kamczyc, J., Witkowski, R., Venanzi, R., & Jagodziński, A. M. (2025). Insufficient logging intervals impede upper soil recovery in temperate beech forests: Insights from two case-studies in poland. *Ecology and Evolution*, *15*(10), e72302. https://doi.org/10.1002/ece3.72302

Lee, S., & McCann, L. (2019). Adoption of cover crops by u.s. soybean producers. *Journal of Agricultural and Applied Economics*, *51*(4), 527–544. https://doi.org/10.1017/aae.2019.20

Lemke, S., Smith, N., Thiim, C., & Stump, K. (2024). Drivers and barriers to adoption of regenerative agriculture: Cases studies on lessons learned from organic. *International Journal of Agricultural Sustainability*, *22*(1), 2324216. https://doi.org/10.1080/14735903.2024.2324216

Levins, R., & Lewontin, R. (1980). Dialectics and reductionism in ecology. *Synthese*, *43*(1), 47–78. https://doi.org/10.1007/BF00413856

Levy, G. J., & Miller, W. P. (1997). Aggregate stabilities of some southeastern u.s. soils. *Soil Science Society of America Journal*, *61*(4), 1176–1182. https://doi.org/10.2136/sssaj1997.03615995006100040024x

Lind, L., Harbicht, A., Bergman, E., Edwartz, J., & Eckstein, R. L. (2022). Effects of initial leaching for estimates of mass loss and microbial decomposition—call for an increased nuance. *Ecology and Evolution*, *12*(8), e9118. https://doi.org/10.1002/ece3.9118

Liptzin, D., Norris, C. E., Cappellazzi, S. B., Bean, G. M., Cope, M., Greub, K. L., Rieke, E. L., Tracy, P. W., Aberle, E., Ashworth, A., Bañuelos Tavarez, O., Bary, A. I., Baumhardt, R., Borbón Gracia, A., Brainard, D. C., Brennan, J. R., Briones Reyes, D., Bruhjell, D., Carlyle, C. N., . . . Honeycutt, C. W. (2022). An evaluation of carbon indicators of soil health in long-term agricultural experiments. *Soil Biology and Biochemistry*, *172*, 108708. https://doi.org/10.1016/j.soilbio.2022.108708

Lobry De Bruyn, L. A. (2019). Learning opportunities: Understanding farmers' soil testing practice through workshop activities to improve extension support for soil health management. *Soil Use and Management*, *35*(1), 128–140. https://doi.org/10.1111/sum.12466

Luján Soto, R., De Vente, J., & Cuéllar Padilla, M. (2021). Learning from farmers' experiences with participatory monitoring and evaluation of regenerative agriculture based on visual soil assessment. *Journal of Rural Studies*, *88*, 192–204. https://doi.org/10.1016/j.jrurstud.2021.10.017

Lupwayi, N. Z., Clayton, G. W., O'Donovan, J. T., Harker, K. N., Turkington, T. K., & Rice, W. A. (2004). Decomposition of crop residues under conventional and zero tillage. *Canadian Journal of Soil Science*, *84*(4), 403–410. https://doi.org/10.4141/S03-082

McDaniel, M. D., Mohammadiarvejeh, P., Hu, G., & Middleton, T. E. (2025). What regulates decomposition in agroecosystems? insights from reading the tea leaves. *Frontiers in Sustainable Food Systems*, *9*, 1665233. https://doi.org/10.3389/fsufs.2025.1665233

McDaniel, M., Grandy, A., Tiemann, L., & Weintraub, M. (2014). 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

McKinley, D. C., Miller-Rushing, A. J., Ballard, H. L., Bonney, R., Brown, H., Cook-Patton, S. C., Evans, D. M., French, R. A., Parrish, J. K., Phillips, T. B., Ryan, S. F., Shanley, L. A., Shirk, J. L., Stepenuck, K. F., Weltzin, J. F., Wiggins, A., Boyle, O. D., Briggs, R. D., Chapin, S. F., . . . Soukup, M. A. (2017). Citizen science can improve conservation science, natural resource management, and environmental protection. *Biological Conservation*, *208*, 15–28. https://doi.org/10.1016/j.biocon.2016.05.015

Middelanis, T., Pohl, C. M., Looschelders, D., & Hamer, U. (2023). New directions for the tea bag index: Alternative teabags and concepts can advance citizen science. *Ecological Research*, *38*(5), 690–699. https://doi.org/10.1111/1440-1703.12409

Middleton, T. E., McCombs, A. L., Gailans, S. R., Carlson, S., Karlen, D. L., Moore, K. J., Liebman, M. Z., Kaspar, T. C., Al-Kaisi, M. M., Laird, D. A., Wiedenhoeft, M. H., Delate, K., Cambardella, C. A., Thompson, M. L., Heaton, E. A., & McDaniel, M. D. (2021). Assessing biological soil health through decomposition of inexpensive household items. *Applied Soil Ecology*, *168*, 104099. https://doi.org/10.1016/j.apsoil.2021.104099

Miner, G. L., Delgado, J. A., Ippolito, J. A., & Stewart, C. E. (2020). Soil health management practices and crop productivity. *Agricultural & Environmental Letters*, *5*(1), e20023. https://doi.org/10.1002/ael2.20023

Mori, T. (2022a). Validation of the tea bag index as a standard approach for assessing organic matter decomposition: A laboratory incubation experiment. *Ecological Indicators*, *141*, 109077. https://doi.org/10.1016/j.ecolind.2022.109077

Mori, T. (2022b). Is the tea bag index (TBI) useful for comparing decomposition rates among soils? *Ecologies*, *3*(4), 521–529. https://doi.org/10.3390/ecologies3040038

Mori, T., Aoyagi, R., Taga, H., & Sakai, Y. (2021). Effects of water content and mesh size on tea bag decomposition. *Ecologies*, *2*(1), 175–186. https://doi.org/10.3390/ecologies2010010

Natural Resources Conservation Service. (n.d.). *Soil health*. Retrieved March 26, 2026, from https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soil/soil-health

New Mexico Climate Center. (2026). ZiaMet weather station network. Retrieved January 26, 2026, from https://weather.nmsu.edu/ziamet/

Nielsen, B. (2008). A practical guide to on-farm research.

Nimmo, E. R., Nelson, E., Gómez-Tovar, L., García, M. M., Spring, A., Lacerda, A. E. B., De Carvalho, A. I., & Blay-Palmer, A. (2023). Building an agroecology knowledge network for agrobiodiversity conservation. *Conservation*, *3*(4), 491–508. https://doi.org/10.3390/conservation3040032

Noble Strohm, T., Fonte, S., Ghimire, R., Mikha, M. M., Adebayo, O., Bista, P., Acosta-Martinez, V., Angadi, S., & Schipanski, M. (2025). Soil health indicators for water-limited regions: Evaluating relative sensitivity to compost and cropping intensification. *Journal of Soil and Water Conservation*, *80*(4), 438–458. https://doi.org/10.1080/00224561.2025.2477320

Núñez, A., Ball, R., & Schipanski, M. (2022). Plant and soil microbial responses to irrigation retirement in semiarid cropping systems. *Environmental Research Communications*, *4*(3), 035004. https://doi.org/10.1088/2515-7620/ac59c3

Obour, P. B., Oppong Danso, E., Dorvlo, S. Y., & Arthur, E. (2023). Soil aggregate stability quantified by different methods is unaffected by rice straw biochar in the long term. *Soil Science Society of America Journal*, *87*(5), 1018–1028. https://doi.org/10.1002/saj2.20556

Peña, D. G., Calvo, L., McFARLAND, P., & Valle, G. R. (Eds.). (2017, September 1). *Mexican-origin foods, foodways, and social movements: Decolonial perspectives*. University of Arkansas Press. https://doi.org/10.2307/j.ctt1t89jww

Penniman, L. (2018, October 30). *Farming while black: Soul fire farm's practical guide to liberation on the land* [done written]. Chelsea Green Publishing.

Pires, C. B., Krupek, F. S., Carmona, G. I., Ortez, O. A., Thompson, L., Quinn, D. J., Reis, A. F. B., Werle, R., Kovács, P., Singh, M. P., Hutchinson, J. M. S., Ruiz Diaz, D., Rice, C. W., & Ciampitti, I. A. (2024). Perspective of US farmers on collaborative on-farm agronomic research. *Agronomy Journal*, *116*(3), 1590–1602. https://doi.org/10.1002/agj2.21560

Potthoff, M., & Loftfield, N. (1998). How to quantify contamination of organic litter bag material with soil? *Pedobiologia*, *42*(2), 147–153. https://doi.org/10.1016/S0031-4056(24)00413-X

Prairie, A. M., King, A. E., & Cotrufo, M. F. (2023). Restoring particulate and mineral-associated organic carbon through regenerative agriculture. *Proceedings of the National Academy of Sciences*, *120*(21), e2217481120. https://doi.org/10.1073/pnas.2217481120

Python Software Foundation. (n.d.). *Python language reference* (Version 3.12). http://www.python.org

Ragsdale, J. W. (2021). The aboriginal land and water rights of the jemez pueblo. *Denver University Water Law Review 109*, *24*(2). https://irlaw.umkc.edu/faculty_works/646

Ramirez, K. S., Leff, J. W., Barberán, A., Bates, S. T., Betley, J., Crowther, T. W., Kelly, E. F., Oldfield, E. E., Shaw, E. A., Steenbock, C., Bradford, M. A., Wall, D. H., & Fierer, N. (2014). Biogeographic patterns in below-ground diversity in new york city's central park are similar to those observed globally. *Proceedings of the Royal Society B: Biological Sciences*, *281*(1795), 20141988. https://doi.org/10.1098/rspb.2014.1988

Rieke, E. L., Bagnall, D. K., Morgan, C. L., Flynn, K. D., Howe, J. A., Greub, K. L., Mac Bean, G., Cappellazzi, S. B., Cope, M., Liptzin, D., Norris, C. E., Tracy, P. W., Aberle, E., Ashworth, A., Bañuelos Tavarez, O., Bary, A. I., Baumhardt, R., Borbón Gracia, A., Brainard, D. C., . . . Honeycutt, C. W. (2022). Evaluation of aggregate stability methods for soil health. *Geoderma*, *428*, 116156. https://doi.org/10.1016/j.geoderma.2022.116156

Robertson, G. P., Hutson, M. A., Evans, F. C., & Tiedje, J. M. (1988). Spatial variability in a successional plant community: Patterns of nitrogen availability. *Ecology*, *69*(5), 1517–1524. https://doi.org/10.2307/1941649

Rodgers, H., Link, E., Shilpakar, C., Jackson, E., Porensky, L. M., Miner, G. L., & Sebade, B. (2026). Recommendations for on-farm research. *In press*.

Roesch-McNally, G. E., Basche, A. D., Arbuckle, J., 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. https://doi.org/10.1017/S1742170517000096

Röling, N. (1985). EXTENSION SCIENCE: INCREASINGLY PREOCCUPIED WITH KNOWLEDGE SYSTEMS*. *Sociologia Ruralis*, *25*(3), 269–290. https://doi.org/10.1111/j.1467-9523.1985.tb00766.x

Rosenzweig, S. T., Fonte, S. J., & Schipanski, M. E. (2018). Intensifying rotations increases soil carbon, fungi, and aggregation in semi-arid agroecosystems. *Agriculture, Ecosystems & Environment*, *258*, 14–22. https://doi.org/10.1016/j.agee.2018.01.016

Rosenzweig, S. T., Stromberger, M. E., & Schipanski, M. E. (2018). Intensified dryland crop rotations support greater grain production with fewer inputs. *Agriculture, Ecosystems & Environment*, *264*, 63–72. https://doi.org/10.1016/j.agee.2018.05.017

Rossi, E. S., Materia, V. C., Caracciolo, F., Blasi, E., & Pascucci, S. (2023). Farmers in the transition toward sustainability: What is the role of their entrepreneurial identity? *Frontiers in Sustainable Food Systems*, *7*, 1196824. https://doi.org/10.3389/fsufs.2023.1196824

Rothschild, N. A. (2008). The colonial southwest: Pueblo landscapes and spanish shared and separate landscapes. In *Lozny, l.r. (eds) landscapes under pressure. springer, boston, MA.* https://doi.org/10.1007/0-387-28461-3_3

Rust, N. A., Stankovics, P., Jarvis, R. M., Morris-Trainor, Z., De Vries, J. R., Ingram, J., Mills, J., Glikman, J. A., Parkinson, J., Toth, Z., Hansda, R., McMorran, R., Glass, J., & Reed, M. S. (2022). Have farmers had enough of experts? *Environmental Management*, *69*(1), 31–44. https://doi.org/10.1007/s00267-021-01546-y

Ryan, S. F., Adamson, N. L., Aktipis, A., Andersen, L. K., Austin, R., Barnes, L., Beasley, M. R., Bedell, K. D., Briggs, S., Chapman, B., Cooper, C. B., Corn, J. O., Creamer, N. G., Delborne, J. A., Domenico, P., Driscoll, E., Goodwin, J., Hjarding, A., Hulbert, J. M., ... Dunn, R. R. (2018). The role of citizen science in addressing grand challenges in food and agriculture research. *Proceedings of the Royal Society B: Biological Sciences*, *285*(1891), 20181977. https://doi.org/10.1098/rspb.2018.1977

Sachet, E., Mertz, O., Le Coq, J.-F., Cruz-Garcia, G. S., Francesconi, W., Bonin, M., & Quintero, M. (2021). Agroecological transitions: A systematic review of research approaches and prospects for participatory action methods. *Frontiers in Sustainable Food Systems*, *5*, 709401. https://doi.org/10.3389/fsufs.2021.709401

Sands, B., Machado, M. R., White, A., Zent, E., & Gould, R. (2023). Moving towards an anti-colonial definition for regenerative agriculture. *Agriculture and Human Values*, *40*(4), 1697–1716. https://doi.org/10.1007/s10460-023-10429-3

Sarneel, J. M., Barel, J. M., Duddigan, S., Keuskamp, J. A., Pastor, A., Sandén, T., & Blume-Werry, G. (2023). Reasons to not correct for leaching in TBI ; reply to lind et al. (2022). *Ecology and Evolution*, *13*(6), e10133. https://doi.org/10.1002/ece3.10133

Schneider, S. A. (n.d.). *Discrimination in agriculture* [Food, farming & sustainability: Readings in agricultural law]. Retrieved February 25, 2024, from https://www.foodfarmingsustainability.com/discrimination-in-agriculture

Semenov, M. V., Zhelezova, A. D., Ksenofontova, N. A., Ivanova, E. A., Nikitin, D. A., & Semenov, V. M. (2025). Microbiological indicators for assessing the effects of agricultural practices on soil health: A review. *Agronomy*, *15*(2), 335. https://doi.org/10.3390/agronomy15020335

Singh, P., Kawa, N. C., & Sprunger, C. D. (2024). “more questions than answers”: Ohio farmers’ perceptions of novel soil health data and their utility for on-farm management. *Agroecology and Sustainable Food Systems*, *48*(1), 74–92. https://doi.org/10.1080/21683565.2023.2270928

Six, J., Elliott, E., & Paustian, K. (2000). Soil macroaggregate turnover and microaggregate formation: A mechanism for c sequestration under no-tillage agriculture. *Soil Biology and Biochemistry*, *32*(14), 2099–2103. https://doi.org/10.1016/S0038-0717(00)00179-6

Soil Survey Staff, Natural Resources Conservation Service, & United States Department of Agriculture. (2026). Web soil survey.

Tisdall, J. M., & Oades, J. M. (1982). Organic matter and water-stable aggregates in soils. *Journal of Soil Science*, *33*(2), 141–163. https://doi.org/10.1111/j.1365-2389.1982.tb01755.x

University of East Anglia Climatic Research Unit, Harris, I.C., Jones, P.D., & Osborn, T. (2025). CRU TS4.09: Climatic research unit (CRU) time-series (TS) version 4.09 of high-resolution gridded data of month-by-month variation in climate (jan. 1901- dec. 2024). [https://ceda-wps-ui.ceda.ac.uk/processes]. https://catalogue.ceda.ac.uk/uuid/9cf07e92afaa405da4f40b6733f362d3

Vandermeer, J., & Perfecto, I. (2017). Ecological complexity and agroecosystems: Seven themes from theory. *Agroecology and Sustainable Food Systems*, *41*(7), 697–722. https://doi.org/10.1080/21683565.2017.1322166

Vanloqueren, G., & Baret, P. V. (2009). How agricultural research systems shape a technological regime that develops genetic engineering but locks out agroecological innovations. *Research Policy*, *38*(6), 971–983. https://doi.org/10.1016/j.respol.2009.02.008

Victoria, M., Leggette, H., Foster, J., Orem, M., Neely, C., Neely, H., & Palmer, K. (2025). Exploring wheat farmers' soil health management practices, adoption characteristics, and information preferences. *Journal of Applied Communications*, *109*(1). https://doi.org/10.4148/1051-0834.2554

Vitullo, T. (2026). *Mistral long transcriber: Multimedia transcriptions with search using mistral's voxtral and lunr.js* [Anti-disinfo]. Retrieved April 20, 2026, from https://anti-disinfo.si/posts/voxtral_transcribe/

Waithaka, M. (2005). Communication for rural innovation: Rethinking agricultural extension. *Agricultural Systems*, *84*(3), 359–361. https://doi.org/10.1016/j.agsy.2004.10.002

Walder, F., Büchi, L., Wagg, C., Colombi, T., Banerjee, S., Hirte, J., Mayer, J., Six, J., Keller, T., Charles, R., & Van Der Heijden, M. G. A. (2023). Synergism between production and soil health through crop diversification, organic amendments and crop protection in wheat-based systems. *Journal of Applied Ecology*, *60*(10), 2091–2104. https://doi.org/10.1111/1365-2664.14484

White, D. C., Davis, W. M., Nickels, J. S., King, J. D., & Bobbie, R. J. (1979). Determination of the sedimentary microbial biomass by extractible lipid phosphate. *Oecologia*, *40*(1), 51–62. https://doi.org/10.1007/BF00388810

Wickings, K., Stuart Grandy, A., Reed, S., & Cleveland, C. (2011). Management intensity alters decomposition via biological pathways. *Biogeochemistry*, *104*(1), 365–379. https://doi.org/10.1007/s10533-010-9510-x

Wienhold, B., Pikul, J., Liebig, M., Mikha, M., Varvel, G., Doran, J., & Andrews, S. (2006). Cropping system effects on soil quality in the great plains: Synthesis from a regional project. *Renewable Agriculture and Food Systems*, *21*(1), 49–59. https://doi.org/10.1079/RAF2005125

Wilpiszeski, R. L., Aufrecht, J. A., Retterer, S. T., Sullivan, M. B., Graham, D. E., Pierce, E. M., Zablocki, O. D., Palumbo, A. V., & Elias, D. A. (2019). Soil aggregate microbial communities: Towards understanding microbiome interactions at biologically relevant scales. *Applied and Environmental Microbiology*, *85*(14), e00324–19. https://doi.org/10.1128/AEM.00324-19

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 (L. A. N. Amaral, Ed.). *PLoS ONE*, *9*(8), e105203. https://doi.org/10.1371/journal.pone.0105203

Yang, H., Yuan, Y., Zhang, Q., Tang, J., Liu, Y., & Chen, X. (2011). Changes in soil organic carbon, total nitrogen, and abundance of arbuscular mycorrhizal fungi along a large-scale aridity gradient. *CATENA*, *87*(1), 70–77. https://doi.org/10.1016/j.catena.2011.05.009

Yost, J. L., Kruger, K., Bjorneberg, D. L., Dungan, R. S., Leytem, A. B., Moore, A. D., & Schott, L. R. (2024). Assessment of soil aggregate stability methodologies in calcareous silt loams. *Journal of the ASABE*, *67*(4), 879–887. https://doi.org/10.13031/ja.15650

Yuan, M., Burjel, J. C., Martin, N. F., Isermann, J., Goeser, N., & Pittelkow, C. M. (2021). Advancing on-farm research with UAVs: Cover crop effects on crop growth and yield. *Agronomy Journal*, *113*(2), 1071–1083. https://doi.org/10.1002/agj2.20546