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Publication Date
2023

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By

Ansel Olive Klein

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Environmental Science, Policy, and Management

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Timothy Bowles, Chair
Professor Celine Pallud
Professor Liz Carlisle

Spring 2023

Abstract

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Healthy soils are the basis for resilient agricultural systems. Yet, on *working* organic farms in the United States, disentangling the features of soil management that support agricultural resilience remains a key challenge. Importantly, available soil indicators have facilitated efforts to measure expression of soil health on-farm. Despite the widespread focus on quantitative soil indicators, farmers—who are closest to the land, and soil—have been largely omitted from research on soil health. However, if available soil indicators are to be considered effective by farmers, they must be grounded in farmers' realities and local soil contexts. Engaging with farmer knowledge of soil—and farmers' approaches to soil management *in practice*—therefore represents an important and underutilized opportunity to widen our research frame around how assessment of and management of soil on farms is realized. In this dissertation, I take a case study approach, focusing on 13 unique organic farms in Yolo County, California.

Across three chapters, I investigate three main questions at the intersection of farmer knowledge, soil nutrient dynamics related to soil health expression, and on-farm management—First, how do organic farmers who are engaged in alternative agriculture acquire, translate, and apply knowledge of their soil? Second, how can we better pinpoint soil nutrient dynamics, in particular nitrogen availability to crops, on working organic farms, and also consider the role of management and soil edaphic characteristics in influencing these belowground soil nitrogen processes? Third, how can farmer knowledge enhance current understanding of soil fertility and nutrient management, especially in relation to available indicators for on-farm soil fertility?

In the first chapter, I use in-depth interviews with farmers to present ways in which farmers in this location are thinking about their soil and soil management; in the discussion, I propose a framework for understanding the substance of farmer knowledge and farmer knowledge formation, and I then apply this framework to this modest group of farmers and document farmer knowledge of soil management in the region. In the second chapter, across the same farming community (and a single research station), I create farm typologies based on indicators for soil quality to understand nitrogen cycling and crop nitrogen availability—and the role of management and soil texture in explaining differences in soil quality. Overall, I found significant differentiation among farms based on soil organic matter quality, strongly driven by both recent management and soil edaphic factors; I also found that soil texture may play a more significant role in determining soil organic matter levels, especially compared to management. Finally in the third chapter, I assess the utility of available indicators for soil fertility in informing on-farm management across this same farming community; overall, results underscored the current overemphasis of crop nutrient availability in building on-farm soil fertility, and the importance of calibrating indicators for soil fertility within local soil contexts by working in collaboration with local farmers.

For all the farmers who continue to be in relationship with the land, soil, their communities, and ancestors of the land.

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ACKNOWLEDGEMENTS

I would like to first affirm Indigenous sovereignty. I would also like to acknowledge my complicity in engaging with an institution that maintains white hegemonic power and refuses to acknowledge their role in the real, physical and cultural erasure of Indigenous peoples of the lands that the University of California currently occupies.

I acknowledge that in engaging in this research work, I participated in continuing the colonial legacy of benefiting from the territories of xučyun (Huchiun), the ancestral and unceded land of the Chochenyo-speaking Ohlone people, the successors of the historic and sovereign Verona Band of Alameda County. This stolen land continues to be of great importance to Muwekma Ohlone and Lisjan Ohlone tribal members and other familial descendants of the Verona Band and—more importantly, this land continues to be largely inaccessible to members of the Muwekma Ohlone and Lisjan Ohlone Tribes.

I also acknowledge that I worked with primarily white, and primarily white male farmers located on stolen lands originally home to Patwin-speaking people. Today, this land is still home to the Cachil DeHe Band of Wintun Indians of the Colusa Indian Community, the Kletsel Dehe Wintun Nation, and the Yocha Dehe Wintun Nation. Importantly, these lands continue to be inaccessible and unable to be freely used among members of all three sovereign Indigenous tribes of this region.

In this vein, I affirm and act in solidarity with Black, Brown, and Indigenous land back movements. Land and the ability to use that land in reciprocity with the land and *without restriction* is everything, especially in a place like the United States.

•••

From my undergraduate years at the University of California, Berkeley, I developed a critical eye of academia and the hegemony of science. My sole intention with returning to graduate school was to a carve a small sliver of 'Science' for farmers. All farmers are so wise, so eternally curious, and so brave. For some, being a farmer is not a choice. By design, I worked with a group of majority white farmers, because going into this work, I recognized the extractive and reductionist way in which 'Science' operates. While there exists a large number of Latinx, Indigenous, and Asian American farmers in the region of my research, as a white, immigrant person, I recognized that I did not have the resources to be able to work with these farmers in a way that was not extractive and that did not perpetuate colonial and imperial harm. I equally recognize that as a result, the voices of these farmers is omitted from this research.

Lastly, I acknowledge that farming comes in all forms, not just as perennial and vegetable row crops. Though perhaps a trite example, I know that in the lands local to me, the Coast (Olema) Miwok (Me-Wuk) and Bokeya Pomo people managed, and continue to manage (as permitted by white supremacist laws) their food landscapes in ways that required careful tending and selective harvesting of native food plants; this agriculture does not look like vegetable row crops.

I also recognize that nearly 80% of all foods we access at groceries stores and farmers' markets in the United States today were plants closely cultivated by Indigenous peoples of North America for thousands of years, and that were stolen and subsumed into "American" food culture.

Despite this troubling and complex backdrop, I would like to acknowledge and thank all the farmers that engaged with me and allowed me to listen to their ways of knowing. I feel privileged to have been able to open a window into their understanding of the world of soil and of farming. Thank you for your immense contribution to this body of work that I present in the pages that follow.

COLLABORATORS

The envisioning, shaping, and writing of this dissertation have been a rewarding collaboration, and I would like to name each person that believed in this work and collaborated on this journey. For privacy reasons, I do not name the 13 farmers who also collaborated so deeply on this research; nonetheless, I am ever grateful to each farmer for their openness to collaborate on this body of work and for sharing their deep wisdom. I am also infinitely grateful to…

Cori Hayden & Lisa Conrad,
Faith Kearns,
Kalyn Taylor,
Wendi Bootes,
Liz Carlisle,
Margaret Lloyd,
Celine Pallud,
Nathan Sayre,
Maria Mooshammer,
Oia Walker-Van Aalst,
Zeltzin Angon,
Arely Ortiz,
Karen Arroyo,
Moe Sumino,
Berkeley Agroecology Lab,
Timothy Bowles,
Hannah Waterhouse,
Louise Jackson,
Van Butsic,
Kurt Spreyer,
Patina Mendez,
Christian Cain,
Scott Chang-Fleeman,
Katherine Siegel,
Christine Eleanor Wilkinson,
Phoebe Parker-Shames,
Aidee Guzman,
Leke Hutchins,
Elaine Patarini,
Tara Shi & Ben Lotam,
Kimberly Rodrigues,
Bianca Victorica,

and finally, my trusty blue 1988 Toyota pickup.

PREFACE

This dissertation began as an exercise to widen the frame around how scientists engage in agricultural research. Widening the frame, as Lauret E. Savoy and Alison H. Deming describe in *Colors of Nature: Culture, Identity, and the Natural World*, refers to opening real and metaphoric gates that allow other voices and other ways of knowing not currently included in the dominant, narrow rhetoric of our world today.

In this dissertation, I, in partnership with close collaborators, attempt to widen the frame in how we, as scientists and academic researchers, do agricultural research—in a way that engages with farmers and their knowledge, as part and parcel of the research and the production of science. Because soil is so central to the work of a farmer and their livelihood, I led with curiosity and intentionally centered soil as the starting point for this dissertation work. While farmers are indeed researchers (that largely operate outside of academia), the scope of this dissertation work did not allow for farmers to act as explicit co-authors; nevertheless, in the chapters following, I showcase a few emergent approaches to incorporating farmer voices, and importantly their knowledge, into academic research on agricultural systems and soil science research—particularly as farmer knowledge relates to conceptual and practical aspects of soil health, soil fertility, and soil nutrient dynamics.

The compilation of chapters I present here is but one, very humble and imperfect example for widening the frame of academic research on agricultural systems. It is important to point out that there are already scientists and academic researchers who are working towards widening our research frames in this field. There is also much work to be done, and the process is no doubt hard work. As we do, we must remember to move with care and at the speed of trust; we must actively contribute to thoughtful dismantling of patterns that maintain the status quo; and we must also not be afraid to begin.

CHAPTER I

From theory to practice: Understanding farmer knowledge of soil management among a community of organic farms in northern California

ABSTRACT

Farmer knowledge is an essential component of research in alternative agriculture. In the United States, farmer knowledge, particularly farmer knowledge of soil health and soil management, has been widely underappreciated and underdocumented within the scientific literature—from theory to practice. Applying a case study approach, we interviewed 13 organic farmers based in Yolo County, CA to understand how organic farmers in this region acquire knowledge about their soils, to document what organic farmers in this region know about their soils, and to share key management practices organic farmers use to build soil health in the region. Based on interviews, we found these organic farmers acquire knowledge about their farming systems primarily through direct observation, personal experience, experimentation, and inherited wisdom. To evaluate soil health, farmers cited using a range of indicators, including soil structure, crop health, growth habits of weeds, and soil biology. We found that farmers possess extensive place-based knowledge of their local farming systems and that this knowledge represents an underutilized source for innovation and adaptive management in scientific and policy-making contexts.

INTRODUCTION

Background

Farming is inherently knowledge intensive. This knowledge base is multi-faceted and context-specific, and often informed by scientists, researchers, policymakers, government, extension agents as well as by farmers. While farmer knowledge is a critical component of this knowledge base, in the United States farmer knowledge has been widely underappreciated (Kloppenburg 1991). Long considered "informal" knowledge, farmer knowledge is generally not regarded as scientifically valid and therefore infrequently recorded, whether formally or informally (Knapp and Fernandez-Gimenez 2009).

Since the 1950s, due to an increase in knowledge standardization within production agriculture (whereby technical farming knowledge is considered transferable, scalable, and independent of the local social or environmental context) combined with widespread deskilling among farmers and farmworkers, farmer knowledge has become increasingly undervalued (Timmermann and Felix 2015; Morgan and Murdoch 2000). However, farmers who practice alternative agriculture (eg, agroecological, organic, diversified farming, etc) often amass an incredible wealth and depth of knowledge that integrates multiple ways of knowing and reflects diverse knowledge systems for thinking about evidence; perhaps most importantly, farmer knowledge is based in practice (Sūmane et al. 2018; Millar and Curtis 1997).

If current trends in consolidation of land ownership, chemical-based intensification of agriculture, and standardization of farmer knowledge continue, local farmer knowledge may be endangered or permanently lost (MacDonald 2020; Strauss 2016; Sūmane 2010). Before this occurs, it is essential that we elevate the critical role of farmer knowledge and: 1) understand the key features of farmer knowledge; 2) understand the substance of farmer knowledge; and 3) systematically document farmer knowledge in specific local contexts. Understanding the substance of farmer knowledge serves as a first step to conserve this essential knowledge base in practice; however, it is equally critical to document the particularities of farmer expertise in local contexts to provide essential knowledge for other contemporaneous and future generations of farmers, scientists, and policymakers alike.

Moving forward, there is therefore a need to elevate the importance and value of farmer knowledge across multiple disciplines such that farmer knowledge is considered "expert" knowledge throughout alternative agriculture (Flora 1992; Strauss 2016). While other studies attempt to integrate the artificial binary between "formal" and "informal," or "expert" and "nonexpert" knowledge and view the two forms of knowledge as complementary (Morgan and Murdoch 2000; Oudwater and Martin 2003; Stoate et al. 2019; Adamsone-Fiskovica & Grivins 2021), in this paper we maintain that farmer knowledge is scientifically valid, expert knowledge and therefore warrants formal, standalone documentation within the scientific literature (Thrupp 1989; Collins and Evans 2002; Oliver et al. 2012).

Local knowledge defined

While it is true that the terms “traditional,” “folk,” and/or “indigenous” knowledge are applied in certain contexts, in this paper, the term “local knowledge” is most appropriate (see Antweiler 2019 for table, p.4), as farmer participants were all white and all either first- or second-generation settlers on unceded Patwin-speaking Wintun Nation tribal lands in Yolo County, CA. To frame this paper, we apply Agrawal’s (1995) definition of local knowledge as knowledge that is “integrally linked with the lives of people, always produced in dynamic interactions among humans and between humans and nature, and constantly changing.” This definition of local knowledge recognizes the key elements of local knowledge: 1) It is produced by people and among people; 2) It is always produced in relationship with nature; and 3) It is a dynamic process. More broadly defined, local knowledge involves dynamic processes and complex systems of experiences, practices, and skills developed and sustained by people (and communities) in their environmental and socioeconomic realties (Thrupp 1989; Antweiler 1998; Nygren 1999).

Further, local knowledge may develop even within one or two generations of place-based experience (Maltz 2013). In the US, there exists a handful of studies documenting rural local knowledge (Feldman and Welsh 1995) and rancher local knowledge (Knapp and Fernandez-Gimenez 2009). Very few studies explicitly examine local knowledge in the context of alternative agricultural or organic systems, referred to as “farmer knowledge” in the literature. This type of knowledge is a subset of local knowledge that enables knowledge holders to farm alternatively in their specifical local contexts. To date, most formal studies on farmer knowledge tend to focus on farmer decision making as it relates to the adoption of new practices (Ryan et al. 2010). Few studies exist at the intersection of local knowledge, alternative agriculture, and soil management.

Farmer knowledge of soil management

To consider this gap, we focus this study on a significant epicenter for alternative agriculture in the United States: Yolo County, California, which represents unceded Patwin-speaking Wintun Nation tribal lands. This region in northern California is unique in that it is among the handful of places in the country that emerged as a catalyst and knowledge hub for the organic agriculture movement and where a large concentration of high value, innovative organic production farms continue to thrive today. Due to a unique set of historical and ecological circumstances, the region experienced an influx of organic farmers beginning in the 1970s (see Guthman 2014). During this decade, Yolo County—in combination with Santa Cruz, CA—became a significant node in the organic movement. Its emergence as a significant node was in part due to Yolo County’s proximity to the San Francisco Bay Area (and its markets) and the University of California, Davis—which provided key institutional support—and also partially due to the existence of largely prime agricultural lands (eg, mostly Class I and II soils) combined with a temperate climate ideal for growing year-round.

As a result, Yolo County became one of a few of places where regulations for organic production first evolved and experimentation with organic farming first emerged (Guthman 2014). Following the farm financial crisis of the 1980s, land prices in the County (and across the US) sharply dropped (Barnett 2000); this economic window provided an opportunity for a new generation of farmers to insert a more ecologically-minded approach to farming. Many of these farmers arrived to Yolo County relatively new to farming (eg, one or two generations)—often young, educated white urbanites with a desire to farm alternatively to the industrial agribusinesses that had historically dominated the landscape of Yolo County since the early 1900s (Belasco 1989).

When these so-called "back-to-the-land" farmers arrived, many were particularly interested in soil fertility—a conscious effort to avoid "mining the soil" (as was common in most industrial agriculture at the time) and address ongoing issues with soil degradation in agriculture (Guthman 2014). While initially these back-to-the-landers lacked historically- and ecologically-specific knowledge of the lands they cultivated (Belasco 1989), over the last three decades or more, it is highly probable that they have individually amassed a wealth of local, place-based knowledge of their specific management contexts and soil landscapes (Sūmane et al. 2015; Lincoln and Ardoin 2016). In this sense, farmer knowledge of *soil management* presents a particularly salient entry point for further examination in the context of Yolo County specifically. How did these particular farmers address the challenge of soil management in their region? What have they individually and collectively learned about soil management, in theory and in practice?

Such questions are particularly important to consider given that—from a pedological and agricultural perspective—soils are heterogenous across landscapes. For example, even at the scale of a single field, differences in microenvironments, management histories, inherent soil characteristics, and time of year can all dramatically influence how a particular field can be most effectively managed. Addressing this challenge in soil management and understanding the nuances of soil management are fundamental to organic systems—where deep place-based knowledge of soil landscapes is the basis for building and sustaining healthy soils on-farm—and more broadly, resilient agriculture. Yet, farmer knowledge of soil management is still generally under-researched, particularly in the United States and particularly among organic farmers.

Though documentation of farmer knowledge of soil management in alternative agriculture exists, most studies focus within the "development" context (Beckford and Barker 2007; Kpienbaareh 2020, Oudwater and Martin 2003). Similarly, research on indigenous knowledge of soil is frequently approached from an ethnopedological (Barrera-Bassols 2016) or traditional ecological knowledge (TEK) perspective (Martin et al. 2010; Anderson 2005), and lacks focus on production and/or organic agriculture. To date, farmer knowledge of local soil landscapes and related soil management practices remains entirely undocumented in Yolo County. Yet, the unique historical and ecological context makes farmer knowledge of soil health and soil management in this region especially important to document; this knowledge is potentially foundational as organic farmers adapt their farming approaches and management in the face of increasing social, economic, and environmental uncertainties.

Though many organic farmers in Yolo County are informed by principles of alternative agriculture when managing their soils, it is less clear how these farmers have translated their ethos into practice and the substance of the soil management practices applied. To address this gap, we examined local farmer ethos and practical knowledge of soil management in this region. Our objectives were to: 1) understand how farmers acquire local knowledge of their soils; 2) document what organic farmers know about their soils; and 3) determine how these farmers translate this local knowledge into specific management practices related to soil health and on-farm resilience.

METHODS

Background

This research is informed by a Farmer First approach, which recognizes farmers as experts and crucial partners in researching and innovating solutions for resilient, alternative agriculture (Chambers et al. 1989; Chambers and Ghildyal 1985). The Farmer First approach recognizes multiple knowledge forms and challenges the standard "information transfer" pipeline model that is often applied in research and extension contexts (Scoones and Thompson 1994; Drinkwater et al. 2016). We used an open-ended, qualitative approach that relied on in-depth and in-person interviews to study farmer knowledge. Such methods are complementary to surveys that use quantitative methods for capturing a large sample of responses (Prokopy 2011).

Because they are more open-ended, qualitative approaches allow for more unanticipated directions (King 1998); however, as Scoones and Thompson (1994) point out, removing local knowledge from its local context and attempting to fit it into the constrictive framework of Western scientific rationality is likely to lead to significant errors in interpretation, assimilation, and application. While interviews are not able to capture the quantity of farmer input that surveys do, in-depth interviews allow researchers to access a deeper knowledge base that has inherent value—despite limitations in scalability and/or transferability—as participants respond in their own words, using their own categorization, and perceived associations (Stewart and Shamdasani 2014). Such in-depth interviews are therefore essential to research on farmer knowledge and local knowledge (Prokopy 2011).

Participant recruitment

To identify potential participants for this study, we first consulted the USDA Organic Integrity database (see, https://organic.ams.usda.gov/integrity) and assembled a comprehensive list of all organic farms in the county (N=114). Next, with input from the local University of California Cooperative Extension (UCCE) Small and Organic Farms Advisor for Yolo County, we narrowed the list of potential farms by applying several criteria for this study: grow fruit, vegetables, and other diversified crops; located within Yolo County; at least 10 years of experience in organic farming; at least five years of farming on the same land. This significantly reduced the pool of potential participants; in total, sixteen (N=16) farms were identified to fit the criteria of this study (IRB ID:2018-04-11014).

These 16 farmers were contacted with a letter containing information about the study and its scope; this research was part of a larger project examining soil health on working organic farms in the region. Working with the local UCCE advisor helped to establish trust with farmers identified. Thirteen (N=13) farmers responded and agreed to participate in the entirety of the study (including an initial field visit, in-depth semi-structured interview, and field sampling as part of a parallel study). These organic farmers represent a majority (>80%) of the organic farms growing a diversified array of vegetable and fruit crops that sell to a variety of consumer markets, including farmers' markets, wholesale markets, and restaurants. These farmers interviewed also represented individuals who oversee management and operations on their farms. These individuals were most often the primary owner and operator of the farm, and made key management decisions on their farm. All farms included were located in Yolo County, with the exception of one farm, located on the border of Yolo and Solano Counties.

Interview process

In-person interviews were conducted in the winter, between December 2019 – February 2020; three interviews were conducted in December 2020. We used a two-tiered interview process, where we scheduled an initial field visit and then returned for an in-depth, semi-structured interview. The purpose of the preliminary field visit was to help establish rapport and increase the amount and depth of knowledge farmers shared during the semi-structured interviews. The initial field visit typically lasted one hour and was completed with all thirteen participants. Farmers were asked to walk through their farm and talk more generally about their fields, their management practices, and their understanding of the term "soil health." The field interview also provided an opportunity for open dialogue with farmers regarding management practices and local knowledge (Morris 2006). Because local knowledge is often tacit, the field component was beneficial to connect knowledge shared to specific fields and specific practices.

After the initial field visits, all 13 farmers were contacted to participate in a follow up visit to their farm that consisted of a semi-structured interview followed by a brief survey. The semi-structured interview is the most standard technique for gathering local knowledge (Huntington 1998). These in-depth interviews allowed us to ask the same questions of each farmer so that comparisons between interviews could be made. To develop interview questions for the semi-structured interviews (see Appendix, Supplement A), we established initial topics such as the farmer's background, farm history, general farm management and soil management approaches. We consulted with two organic farmers (located in Marin County, CA) to develop final interview questions. The final format of the semi-structured interviews was designed to encourage deep knowledge sharing. For example, the interview questions were structured such that questions revisited topics to allow interviewees to expand on and deepen their answer with each subsequent version of the question. Certain questions attempted to understand farmer perspectives from multiple angles and avoided scientific jargon or frameworks whenever possible. Most questions promoted open-ended responses to elicit the full range of possible responses from farmers.

In the interviews, we posed questions about the history and background of the participant and their farm operation, how participants learned to farm, and to describe this process of learning in their own words, as well as details about their general management approaches. Farmers were encouraged to share specific stories and observations that related to specific questions. Next, we asked a detailed set of questions about their soil management practices, including specific questions about soil quality and soil fertility on their farm. In this context, soil quality focused on ecological aspects of their soil's ability to perform key functions for their farm operation (Doran and Parkin 1994); while soil fertility centered on agronomic aspects of their soils' ability to sustain nutrients necessary for production agriculture (Stockdale et al. 2002). A brief in-person survey that asked a few demographic questions was administered at the end of the semi-structured interviews. Interviews were conducted in person on farms to ensure consistency and to help put farmers at ease. The interviews typically lasted two hours and were recorded with permission from the interviewee.

Data analysis

Interviews were transcribed, reviewed for accuracy, and uploaded to NVivo 12, a software tool used to categorize and organize themes systematically based on research questions (Maher et al. 2018). Coding is a commonly used qualitative analysis technique that allows researchers to explore, understand, and compare interviews by tracking specific themes (Neuman and Kreuger 2003). Through structured analysis of the interview transcripts, we identified key themes and constructed a codebook to delineate categories of knowledge.

Once initial coding was complete, we reviewed quotations related to each code to assess whether the code was accurate. The final analysis included both quantitative and qualitative assessments of the coded entries. For the quantitative measure, we tallied both the number of coded passages regarding different themes or topics, and the number of farmers who addressed each theme. In addition, we examined the content of the individual coded entries to understand the nature of farmer knowledge and consensus or divergence among farmer responses for each theme.

RESULTS

The following results represent the collective pool of knowledge from the organic farmers involved in this study, based on their responses to interview questions. Consequently, these results only identify and characterize general types of knowledge that these 13 farmers shared during interviews but does not fully encompass all types of knowledge that these particular farmers possess. Most importantly, these farmers are not necessarily representative of all organic farmers within their region, or beyond. Below, we introduce farmer demographics, situate farmer knowledge in terms of their connection to the land, and provide insight on how farmers accumulate knowledge; finally, we synthesize key themes that emerged from farmer interviews with regards to soil management.

Farmer demographics

The interview pool of 13 organic farmers included 10 men and 3 women between the ages of 45 to 70. Nearly all farmers were white (N=12), and nearly all farmers (N=12) had postsecondary education. In addition, each farmer interviewed was actively managing their farm at the time of the interview and represented the primary decision maker on the farm. Most farmers (N=11) either grew up on a farm and/or had worked on a farm prior to assuming farm management at their current farm operation. Only three farmers were second generation farmers, and the remainder (N=10) were first generation farmers. All farmers had been farming for at least a decade, and most farmers (N=11) had been farming for at least three decades, typically on the same lands. Nearly half (N=6) of the farmers expressed they were at a big turning point in their personal lives when they decided to farm full time (eg, deciding their next career move, moving across country, etc).

Connection to the land

Farmers possess embedded knowledge, which is knowledge that comes from living on the land and observing natural processes (Knapp and Fernandez-Gimenez 2009). To situate this type of knowledge in this particular place (ie, Yolo County), farmers described their relationship to the land they farmed. Not surprisingly, many farmers initially responded with personifications of their land (eg, “I see it as a living organism;” “You have to be able to listen to your land;” “The land has its own life force;” “The land sets all the rules. As a farmer, you have to be able to listen to what your land is telling you and try not to piss it off too much.”).

Initial responses also spoke to farmer perception of their role within the land (eg, “I belong to the land more than it belongs to me;” “I am a liaison between this piece of land and the human environment;” “I am a fellow traveler on this land;”) as well as an expression of romanticism for their land (eg, “I love where we are;” “I love my land;” “The land is very much a gift.”). Several farmers (N=5) characterized their role as a responsibility (eg, “If you don’t take care of the land, it won’t take care of you;” “I would love to take better care of the land;” “I feel responsible to try to improve it and enhance it, and really not to degrade it in any way;” “It’s my turn to steward the land and to leave this place as good or better than I found it; hopefully better!” “I feel a strong sense of responsibility to the land.”). Among farmers who owned most of the land that they farmed (N=11), there was a distinct lack of reference to land ownership; these farmers described their relationship both as a responsibility and as part of a larger human inheritance.

Farmer knowledge formation

Farmers accumulated knowledge through four primary mechanisms: personal experience, experimentation, direct observation, and inherited wisdom.

Direct experience and experimentation

All farmers interviewed (N=13) mentioned direct experience as being one of the most important modes for understanding their landscape, their farming system, and management practices essential to their farm operation. Farmers described this accumulation of experience as "learning by doing," being "self-taught," or learning by "trial and error" (also "hands on" or "applied" learning). These farmers added that in learning by experience, they made "a lot of mistakes" and/or faced "many failures" but also learned from these mistakes and failures—and importantly, that this cycle was crucial to their chosen learning process.

More than half of the farmers interviewed (N=7) maintained that no guidebook or manual for farming exists; while reading books was viewed as valuable and worked to enhance learning for individual farmers, to *farm* required knowledge that could only be gained through experience. Moreover, nearly all farmers also explicitly commented on the fact that they have never stopped learning to farm (eg, "I would also say that I've never stopped learning to farm;" "I don't think that the intensity of the learning curve changes over time."). Overall, farmers learned primarily through personal experience and over time, making connections and larger conclusions from these experiences.

On-farm experimentation was a critical component of knowledge building as well. For these farmers, experimentation consisted of on-farm methodical trials implemented at small scales, most often directly on a small portion of their fields. Experimentation was often incited by observation (of phenomena on the farm or other local farms), a desire to learn, increased alignment with their own ethos, or a need to pivot in order to adapt to external changes. Farmers experimented to test the feasibility of implementing specific incremental changes to their current farming practices before applying these changes across their entire farm.

For example, one farmer relied exclusively on trucking in urban green waste compost as part of the farm's fertility program when she first started farming. However, one year, she decided to allow chickens to roam in a few of the fields; within a few years, those fields were outproducing any other field on farm, in terms of crop yield. She quickly transitioned the entire farm away from importing green waste compost to rotating chickens on a systematic schedule throughout all fields on her farm. This form of experimentation allowed this farmer to move from relying on external inputs for fertility to cycling existing resources within the farm and creating an internally regulated farming system (Peterson et al. 2018). For this farmer, this small experiment was monumental and shifted her entire farm towards a management system that was more in alignment with her personal farming ethos. As she described, "When you look at everything on the farm from a communal perspective and apply that concept of community to everything on the farm… it literally applies to every aspect of your life too.”

Another farmer shared that he had been farming for over two decades when he decided to move away from making raised, shaped beds to prepare his land each season. He described,

> For the longest time, I used raised beds. I looked at the tomato grower across the road. He had these nice beds, flat across the top. Beautifully shaped furrows, perfect. I thought, that must be the way you do things to get these raised beds. So, I got the bed shaper and made these raised beds. They weren't quite as neat as the tomato guys. But then, years later, I thought, ‘Why am I doing this?’ Usually, the rationale for raised beds is drainage in the winter time. You can use them for furrow irrigation, if you furrow irrigate. It warms up a little faster in the Spring. And they guide a cultivating sled. So if you're cultivating with a cultivating sled, then it has some purpose; or if you also plant that way, then you can cultivate really closely. I wasn't doing any of those things. So, why am I going through all this rigmarole to make these raised beds? For me that was one of those unexamined things in my life: this is what everyone is doing so I'll do it too. Then when I actually got to thinking about it, I said I don't actually need to do this. So I just started farming on flat ground, row by row I tried no beds. And now I farm on flat ground. I made that transition within the last four or five years.

Though this farmer had initially used direct observation (see section below) to implement raised beds on his farm, as he learned the purpose of raised beds through his own direct experience, he slowly realized—over the course of decades—that raised beds served no purpose for his application. One year, he decided not to shape some of his beds. At the end of the season, he evaluated no real impact on his ability to cultivate or irrigate the row crops on flat ground, and no impact on yield or crop health. In fact, he observed less soil compaction and more aeration due to fewer passes with heavy machinery; and, he saved time and fuel. The transition to farm on flat ground took several seasons for this farmer, but over time, his entire farm operation no longer used raised beds to grow row crops. This breakthrough in farming was informed by personal experience and guided by careful experimentation.

Direct observation and inherited wisdom

Second to experience, observation also influenced the farmer learning process. Whereas direct experience is usually immersive, and embedded within a larger social context, observation is a detached, mechanical form of knowledge production, where a farmer registers what they perceive to transpire (Platt 1983). For example, farmers cited observing other farmers in a multitude of ways: “By watching other farmers, I really mean I’d just drive around and look. I’d see what tools they were using;” or “If I saw someone working in the field, I would stop my car on the side of the road to see what people are doing;” or “I really would just observe my father farm,” as well as making observations about the status of their land (“I walk around every place and I look at it, that is my daily walk”). Several farmers summed up their cycle of learning as a cycle of observation, trial, feedback, observation, trial, feedback, etc (eg, “Do things, they don’t work, so I talk to people, copy people, try your own ideas;” “You make mistakes and you learn by those. I think it’s a lot of observation.”).

Farmers frequently mentioned fellow farmers as a source of learning as well. However, several farmers clarified that this type of learning did not necessarily involve talking to fellow farmers. One farmer shared that he learned certain farming practices from a neighbor farmer through distant observation and then borrowed ideas he subsequently applied on his farm; to achieve this, he admitted that he had never really talked to the other farmer directly. Another farmer noted that he would “go back at night if they [another farmer] left their equipment in the field and just study how it was set up, so I could see what was going on.” Based on interviews with other farmers, farmer-to-farmer knowledge exchange often consisted of detached observation rather than personal conversation or direct contact with another farmer.

However, direct contact and conversation *with older mentors* did play a significant part in the learning process for most farmers (N=11), defined in this paper as inherited wisdom. One farmer remarked in detail of a mentor, “Buster,”

> Buster was this great old codger who was known as a really unhappy, unhelpful guy; but I always found him very helpful. He was helpful to me. We now farm a lot of ground he used to farm. He loved to sit and watch me work in his pickup truck, in his later years, when he wasn't doing so well. He would just give me a list of ‘what I would do’s …’ He wasn't very subtle about telling me what I was doing wrong; and he wasn't an organic farmer, but he was very wise. He gave me a lot of his perceptions and his wisdom about these pieces of ground before I started farming them. He knew where all the funky spots were; he knew where you're going to bury a tractor if you go in in the Spring, when you thought it was ready to go in.

For a majority of farmers, older mentors were identified as key in their development as a farmer. Nearly all farmers (N=11) interviewed mentioned an important older mentor early in their career that helped them to learn the foundations of farming. A few farmers mentioned the importance of having a mentor that was a generation older to accommodate for the “experience gap.” Among farmers interviewed, for the most part, more years of farming equated with more experience and “know how.” One farmer explained, “It takes five years for a new grower just to have seen everything *once*.” Just under half of farmers (N=6) expressed concern about finding a new generation of farmers to take over their operation and worried about what would happen if they did not find a farmer from the younger generation. (eg, “My goal as a farmer is to find someone who can take this land and everything we’ve built and keep it from turning into a golf course.”). Several of these farmers (N=4) expressed deep sadness and loss around this likely reality.

Farmer knowledge of soil management

General approaches

Interfacing with soil. Farmers discussed how they view their soils as part of their larger management system. Nearly half of farmers (N=6) responded that they interact with their soil regularly by touching and/or smelling it. These farmers expressed that such a tactile approach allowed them to understand soil moisture, soil structure, and to a degree soil fertility within a particular field, and also permitted them to compare soils throughout their farm across different fields. Three of these farmers stated explicitly that they viewed their soil as alive and/or a living organism.

A few farmers (N=3) did not explicitly touch or smell their soil, but did relate to their soils through general observation (“As a farmer, our tools of measurement are observation.”). For example, one farmer explained, “I certainly am looking over my shoulder when I’m driving a tractor and seeing how it [the soil] is behaving.” The remainder of farmers (N=4) expressed a sense of awe or reverence for their soil (“The more I farm, the more I am amazed at how miraculous soil really is”). These farmers said that they appreciated the mystery of some aspects of soil. One farmer added, “I think soil is magical. I understand that there are all kinds of things going on in it that I don’t understand, and in a way I kind of like that.” For context, the two farmers quoted here both operated 700-800 acre farm operations.

Evaluating soil health. During the initial field visit, farmers shared their definitions of soil health. Across all farmers (N=13), responses appeared mechanical and resembled language disseminated by government entities such as the Natural Resources Conservation Service (USDA-NRCS). As such, most responses emphasized building soil organic matter, promoting biological (eg, microbial and fungal) activity, maximizing diversity, and minimizing soil disturbance. During the in-depth interview, farmers shared specific indicators used to evaluate soil health on their farms. These responses were varied compared to definitions of soil health and were generally based on observation and personal experience.

Generally speaking, farmers (N=9) relied heavily on their crops and on the health of their crops to inform them about the basic health of their soil. In fact, farmers cited using their crop as their foremost indicator for gauging optimum soil health. One farmer shared, “Mostly, I'm looking at the plants, if the color of green on a particular leaf goes from shiny to matte, or slightly grey undertone to it. These subtle cues, I pick up from just looking at my crops.” The growth habit of weeds within and around fields was also cited as an indicator of soil health. For example, one farmer explained, “I'm looking at how the weeds are growing at the edges of the field, in the middle of the field. Is there a difference between what's happening around the edges and what's happening in the field?”

Some farmers (N=4) also frequently relied on cover crops as indicators for determining soil health and soil behavior. When acquiring new fields, for example, farmers tended to first grow cover crops to establish a baseline for soil health and also understand soil behavior and/or soil type. Farmers used cover crop growth habits to gauge the status of soil health and soil fertility for a particular field before planting the next iteration of crops.

As one farmer elaborated, “I’m judging a field based on how a cover crop grows. It's one thing if you're planting a nutrient-intensive crop in a field, but if you have a cover crop in the field and there's a swath that's this tall and another swatch that’s only this short, then you know there's something seriously different about that section of field and the soil there." Cover crop growth patterns served as an indicator for changing soil management practices as well; for example, one farmer shared,

> I remember—in a way that just staggered me—when in the mid-2000s, we had micro-sprinklers on some land that we were share-cropping, and they had spent all this money on a micro-sprinkler system. You could see in the Fall, the first Fall, the ring that the micro-sprinkler was irrigating. The cover crop we had planted, the cover crop wasn't growing in that ring, even though that area was wetter. There were these rings of salt-toxic soil because the micro-sprinklers had such a high rate of evaporation, the salinity was worse there. But it was because of the cover crops we learned this was happening.

In addition to crop health and cover crop growth patterns, farmers used other biological and physical indicators to determine the health of their soils. Presence (or absence) of "soil life," including earthworms, arthropods, fungi, was used as a key biological indicator of soil health by most farmers (N=11). For most farmers, this was often both a visual and tactile experience; as one farmer described, "Being able to pick up a bunch of soil and see the life in it. If I can see earthworms, if I can see arthropods, if I can see lots of fungus, then I know that's pretty good soil, that that's working well." Not surprisingly, soil structure and soil crumble were also flagged as good physical indicators of soil health by more than half of farmers (N=7). Farmers determined soil structure in a variety of ways, that included: 1) observing soil behavior while on the tractor; 2) touching soil directly, by hand; 3) digging a small hole to observe its vertical profile; or 4) observing how water drains in a field following rain or irrigation. A majority of farmers (N=10) explicitly stated that they did not rely on soil tests to provide information regarding the health or status of their soils.

<u>Managing soil for fields or for crops.</u> When talking about the specifics of soil management, it became clear that there was a fundamental difference in management approach among farmers interviewed. Some farmers (N=2) decided how to manage their soil based on each individual field (eg, applying the same external inputs for fields with similar soil behavior), regardless of the crop history or the type of crop(s) that would grow in the field next. Other farmers did not necessarily take into consideration the underlying soil context or soil type, but instead focused on crop type for the following growing season. This fundamental difference in soil management approach emerged over the course of interviews, where some farmers (N=2) applied a field-based management approach to their soil, while other farmers (N=4) took a crop-based approach to their soil management. This difference in management approach did not correlate with farm size, farmer ethos, or soil type.

<u>Prioritizing timing and appropriate windows.</u> Several (N=4) farmers emphasized the importance of the *timing* of soil management practices. These farmers described critical timing in terms of "appropriate windows." Most often, the issue of timing came up with regards to tillage and optimum soil moisture. The importance of timing also surfaced with regards to type of soil and planting date, for example,

> The heavier soils, you've got smaller windows to operate because if you have normal winter rains, it stays wet longer. Most crops we like to plant as early as possible to minimize summer heat issues on either pollination or fruit set or whatever. So we can't always get in on the heavier clay soils as early as we'd like. So your window of opportunities compared to good soil is much more limited.

For several farmers interviewed, a fundamental part of good soil management was learning these key windows based on their unique environments and accumulated experiences. This place-based knowledge was accrued over time through careful observation and "learning by doing." As one farmer put it, "The soils themselves are not challenging. The challenge is learning about them." This sentiment was shared by several (N=5) farmers.

Key practices

Based on farmer interviews, two key practices emerged as the most central to building healthy soils. First, farmers expressed that maintaining soil structure was the foundation for sustaining soil health and good soil management. Second, farmers also indicated that minimizing external inputs (eg, fertilizers) to create a closed loop system was at the heart of their soil management ethos.

<ins>Maintaining soil structure.</ins> All farmers (N=13) centered discussion of key soil management practices on the importance of maintaining soil structure. While some farmers (N=6) discussed this key management practice in terms of working ground during appropriate windows of soil moisture, other farmers (N=7) talked about their approach in terms of practices that minimize soil compaction (N=6) or promote soil aeration (N=4).

For the former, farmers identified that working their ground during the optimum window of soil moisture was central to maintaining soil structure. As one farmer described this phenomenon, "So basically, when things are too wet you ruin your soil, when things are too dry you ruin your equipment. There's this little space in between (that lasts about 45 minutes) where you can actually get out there and do things just right."

For a large portion of farmers (N=6), determining this optimum window of soil moisture served as the foundation for building and sustaining long-term soil health on their farm. However, learning this window of optimum soil moisture in practice was a process that took years, if not decades; furthermore, to some farmers, learning this feature of optimum soil moisture was more critical than any other aspect of soil management, including nutrient balancing. Repeatedly, farmers cited this soil management practice as a hard learned skill. For example, multiple farmers cautioned with the phrase, "You've got to sit on your hands," in reference to achieving optimum soil moisture. Farmers stressed the importance of never working ground when it is too wet. One farmer detailed the repeated lessons he learned from working his ground too wet,

> A lesson I was taught a number of times, but didn't learn was that you just got to stay out of the field when it's wet. The most critical thing in these soils, in this climate: you've got to sit on your hands, especially if it's Spring and your greenhouses is full of seedlings that need to be in the ground, and you really want to get stuff planted and it's raining. You've just got to sit on your hands you can't get any equipment in the field or you'll ruin it. It took me a long time to finally to get that lesson ingested incorrectly.

This farmer was not alone in his experience. Another farmer described, "The key is knowing when to till on clay soil, and when to stay off of it. My early mistakes was working it too wet." For one farmer, the repercussions were immense and enduring,

> Probably the only time I ever used the word "sin" in my life has to do with working ground. There is what you would call "sinning," where you're out working ground that's just too wet to be worked. And it's a sin because the damage that you can do is – talk about one step forward two steps back – working the ground too wet is one step forward, *five steps back*. You're doing something that's just a real no-no.

Farmers stated that waiting for the "right" soil moisture was key to preserving the workability of their soil. Several farmers pointed out that working soil too wet, even with light machinery, destroyed soil structure for years. As one farmer elaborated,

> The single most important thing is paying attention to your moisture content, because in soil structure, water and horsepower are the two things that have the biggest effect on soil structure. Other things have lots of effects, like roots and life and all that, but the two things that we control, that have a really large effect on soil structure, are horsepower and weight [ie, machinery] and water.

According to farmers interviewed, understanding the appropriate soil moisture to run machinery through fields (whether for planting, tilling, harvesting, etc) was *the* key to maintaining soil structure, and in turn—healthy, productive soils. Farmers also stated that without appropriate soil structure, they observed that nutrients got "locked up" in the soil, root growth was inhibited, and/or presence of earthworms diminished. While determining optimum soil moisture was central to maintaining soil structure for some farmers, other farmers (N=7) touched on the importance of soil structure using a different emphasis; in general, these latter farmers talked about this essential soil management practice in two ways: either minimizing soil compaction or promoting soil aeration.

Some farmers (N=6) discussed minimizing soil compaction in terms of using lighter tools on their fields. One farmer stated that, "We try to keep everything pretty light. We really keep heavy equipment out; our biggest tractors are only 100 horsepower." Another farmer added that timing was a key component to avoiding compaction: "We have lightweight tractors here, no wheels or weights on the tractors, no deep lugs. We used to weight down our discs [disc harrow], but it's not necessary; you just have to wait for the right moment to run the machine."). A third farmer similarly expressed using lighter tools to minimize impact on their ground, saying that, "We are also thinking about weight of tools, a lot of the tractors that we buy are based on the impact that weight has on ground. In general, I think you'll find that we run much lighter equipment than most people because of the impact that weight has on ground."

Lastly, some farmers avoided soil compaction by not planting in certain fields during certain seasons, usually in winter,

> We try to never get out there and compact the soil, if possible, at all. We always compact a little bit, but we try to minimize it. For example, we just wouldn't go out there now [in February]. That's why we don't plant winter crops that need to be harvested in some of these fields;

or,

> This time of year [winter] it's really hard on ground to be out there harvesting carrots or potatoes due to compaction. You're out there with digging forks or with a tractor with a bed lifter, or a potato digger, or whatnot. It's hard on that ground.

Avoiding soil compaction was most commonly mentioned in relation to promoting soil aeration. These farmers did not explicitly talk about using lighter tools, but instead discussed the importance of proactively managing soil in a way that enhanced aeration. To achieve enhanced soil aeration, farmers cited either keeping their ground covered or performing light tillage at the right soil moisture. One farmer described this as, "I have mucked up my ground: I've driven the air out of the soil so it becomes basically unusable for a period of time." To address soil compaction issues, another farmer detailed specific approaches that promoted soil aeration,

> First of all, in the winter, I like to see living green plants and roots in the soil. I like to be getting some root exudates, nourishing soil microorganisms, which gives the worms something to eat. It prevents compaction by rain… A lot of people think about tillage as having to do with killing weeds, or making it easier for the roots of plants to grow, but to me, I'm more interested in the structure of the soil, like is it getting enough oxygen in the soil. I try to create crooked channels of air, about 1/2 mm.

In discussing the importance of soil structure, soil aeration, compaction, and soil moisture were all ultimately interlinked. However as stated, regardless of approach, maintaining soil structure was the foundational principle for safeguarding soil health—across all farmers interviewed.

<u>Minimizing external inputs.</u> Most farmers (N=8) also emphasized the importance of not relying on external inputs, such as importing yard waste compost, manure pellets, bird guano, and other nitrogen-based fertilizers, for soil management. While two of these eight farmers still relied on external inputs to a degree, they shared their ongoing efforts to significantly reduce application of external inputs. To limit external inputs, farmers talked about a range of approaches that included growing cover crops, implementing consistent crop rotations, and/or integrating crop and livestock systems.

Nearly all (N=10) farmers said that planting a regular rotation of cover crops was essential for soil management and for building soil organic matter. No other nitrogen fertilizer or external input could make up for at least one winter cover crop on a field per year, according to multiple farmers (N=5) interviewed. As one farmer put it,

> When you're on a small scale and you have a lot of demand for your product, it's a really hard decision to do any cover crops, because you're sacrificing your income and sales. So deciding to set aside a quarter of the farm to grow cover crop was a difficult decision. So you're making an investment in the soil and it has associated costs with it. But over the long term, it's clear – All of our land that we've been cover cropping and composting over the years, the yields have increased dramatically.

Similarly, another farmer framed the need for cover cropping in terms of persistence—"in the long run persistence pays off; persistence means a lot of cover crop …and giving it time to come alive." The long-term investment of cover crops was a common theme among farmers interviewed. A different farmer explained, "The problem with cover cropping and composting is that it's not always realized in the crop year. So that's why I think with organic agriculture, you're in it for the long haul. You don't get a quick fix."

The application of consistent crop rotations (N=7) was also frequently mentioned in combination with using cover crops. Another farmer explained that proper soil management involved a combination of cover crop and compost in order fuel healthy soil biology, not just soil fertility: "Even when [a field] is fallow, so to speak, we cover crop, which I think of not as passive fallowing, but proactive fallowing. That initial contribution, like cover cropping or application of compost, for me, is way more about microbial population density than it is just simply nutrients, NPK."

While some farmers relied on importing yard waste compost (N=4), a majority (N=8) of farmers raised the issue of the poor quality of yard waste compost in recent years. All of these farmers at one point relied on yard waste compost (usually from urban municipal sources) as part of their fertility program. However, due to increased trash, plastic, and a decrease in the overall quality of yard waste compost – according to farmers – many organic farmers in the area have moved toward phasing out yard waste compost. As one farmer described,

> It's all municipal waste. Some of the facilities don't do a good job of sorting plastics out before so there's a lot of garbage in it which is discouraging and disheartening. It's disgusting. I understand it's hard and you're getting a lot of people who don't necessarily understand or have the time to care about where their compost is going.

In response, farmers have had to pivot to different solutions. For most farmers in this study (N=7), the simplest solution was to move toward integrated crop-livestock systems (ICLS) that rely on chicken, sheep, or cow rotations to supply necessary fertility on their farms. One farmer shared that the transition has been ecologically and economically beneficial for their farm,

> When we first took over this land, we built up the soil with compost from [Waste Management Company] for years and years, but then we found that by moving our chickens through the land, they actually add a good amount of fertility. We stopped using the 'trashy' compost, and switched completely over to the chickens.

Five of the thirteen farmers interviewed have transitioned to ICLS in order to compensate for the reduction of compost in their fertility plans. "I think grazing cows is one of the best ways to build soil," one farmer said. This farmer further elaborated,

> I do really intensive animal rotation; I manage the vegetation in such a way that it builds soil. As the animals rotate, they are depositing sugars and carbon in the soil. In addition, by moving the animals really regularly, you get the more even distribution of the manures and urine contributing to the soil. In a more set stocking rate capacity, there is the water trough and this super manure-toxic zone around it, and your shade tree with another super toxic over-manured area; in contrast, to move the cows regularly creates more evenness in the soil, and is therefore really beneficial to the soil also. I'm pretty intensively feeding and moving my cows, and leaving a lot of manure and mulch out there. This area is totally degraded [previously]; the soil is so messed up over there, so it is really neat to see it improve with animal rotation practices.

It is important to note that despite the transition to integrating livestock into their farm operations, these farmers still primarily consider themselves as "vegetable farmers" and orient their entire operation such that seasonal crops are the focal point for management decisions. It is also important to point out that no farmer explicitly referred to their management approach as an "integrated crop livestock system;" these farmers only casually referred to their integration of animals into their farming approach, perhaps for reasons touched on in the discussion section below.

DISCUSSION

The organic farmers in Yolo County that were interviewed for this study demonstrated wide and deep knowledge of their farming systems. Results show that white, first- and second-generation farmers in alternative agriculture do accumulate substantive local knowledge of their farming systems—even within a decade or two of farming. These particular organic farmers demonstrated a complex understanding of their physical environments, soil ecosystems, and local contexts that expands and complements other knowledge bases (eg, Western science) that inform farming systems. In order to integrate the wide range of knowledge shared in the results, a theoretical framework that incorporates emergent characteristics of the process of farmer knowledge formation is helpful to consider. In the first section of the discussion, we outlined a framework for farmer knowledge formation is outlined. For the latter half of the discussion section, we elaborate on key aspects of farmer knowledge that emerged from results of this study.

A framework for farmer knowledge formation

Understanding the framework

Figure 1 summarizes a proposed theoretical framework for farmer knowledge formation. This framework recognizes the importance of linking social and ecological processes in order to capture interactions between humans and the environment, and is therefore informed by and extends existing frameworks in the social-ecological (SES) literature and can be applied to other farming contexts (Berkes et al. 2000a; Schluter et al. 2019).

The framework encapsulates both social and ecological ways of knowing through an adaptive feedback process, wherein farmers are considered the primary actors in this process of knowledge formation. As shown in Figure 1, farmer knowledge forms through both social and ecological mechanisms. Social mechanisms refer to social and cultural phenomena that influence farmer knowledge and their personal ethos interactively; ecological mechanisms represent how farmers' observations of and experiences with environmental conditions and ecological processes on their farms influences their knowledge and ethos (Berkes et al. 2000a).

Here, farmer ethos is broadly defined as a farmer's worldview on farming—a set of social values or belief system that a farmer aspires to institute on their farm (eg, stewardship ethos, diversified farming ethos, production and efficiency ethos, permaculture ethos, etc) (Bar-Tal 2000). As highlighted in yellow, social mechanisms play a central role in producing a farmer's ethos and in integrating ecological knowledge into their farm operation. At the same time, ecological mechanisms contribute to a farmer's local ecological knowledge base, and importantly, place limits on the incorporation of social values in practice on farms. Together, these social and ecological mechanisms provide the filter through which farmer ethos and ecological knowledge is re-evaluated over time. As outlined in green, farmer ethos also mutually informs ecological knowledge, and vice versa, in a dynamic, dialectical process as individual farmers apply their ethos or ecological knowledge in practice on their farm.

Based on results of this study, social mechanisms include inherited wisdom from and informal conversations with other local farmers (Figure 1). Likewise, direct observation, personal experience, and on-farm experimentation—wherein a farmer applies the scientific method to make abstract science concrete—are central to developing farmers' specific ecological knowledge (Figure 1). In general, farmers interviewed tended to rely less on abstract, "basic" science and more on concrete, "applied" science that is based on their specific local contexts and environment (Lévi-Strauss 1994). In this way, social and ecological mechanisms were key in translating abstract information into concrete knowledge among farmers interviewed. Findings suggest that experimentation codifies direct observations to generate farmer knowledge that is both concrete and transferable. To a lesser degree, personal experience enhanced farmer knowledge and guided the process of experimentation.

Applying the framework

This framework is useful for categorizing and tracking farmer learning on working farms. As an example, farmers with a stewardship ethos viewed themselves as caretakers of their land; one farmer described their role as “a liaison between this piece of land and the human environment.” Farmers that self-identified as stewards or caretakers of their land tended to rely most heavily on direct observation and personal experience to learn about their local ecosystems and develop their local ecological knowledge. This knowledge directly informed how farmers approached management of their farms and the types of management practices and regimes they applied.

That said, farmer ethos did not always completely align with farming practices applied day-to-day due to both social and ecological limits of their environment. For example, one farmer, who considered himself a caretaker of his land expressed that cover crops were central to his management regime and that “we've underestimated how much benefit we can get from cover crops.” This same farmer admitted he had not been able to grow cover crops the last few seasons due to early rains, heavy clay in his soil, and the need to have crops ready for early summer markets.

In another example, several farmers learned about variations in their soil type by directly observing how soil “behaved” using cover crop growth patterns. These farmers discussed that they learned about patchy locations in their fields, including issues with drainage, prior management history, soil type, and other field characteristics, through observation of cover crop growth in their fields. Repeated observations over space and time helped to transform disparate observations into formalized knowledge. As observations accumulated over space and time, they informed knowledge formation across scales, from specific features of farmers’ fields to larger ecological patterns and phenomena.

More broadly, using cover crop growth patterns to assess soil health and productivity allowed several farmers to make key decisions that influenced the long-term resilience of their farm operation (eg, only plant cash crops in areas of a field where cover crops grew tall in the previous season and leave other areas under pasture for another season or two *rather than* apply compost throughout all fields). This specific adaptive management technique was developed independently by several farmers over the course of a decade of farming through long-term observation and experimentation and, at the time, was not widely accessible in farming guidebooks, policy recommendations, or the scientific literature. For these farmers, growing a cover crop on new land or land with challenging soils is now formally part of their farm management program and central to their soil management.

While some farmers considered this process “trial and error,” in actuality, all farmers engaged in a structured, iterative process of robust decision making in the face of constant uncertainty, similar to the process of adaptative management in the natural resource literature (Holling 1978; Berkes et al. 2000b). This critical link to adaptative management is important to consider in the broader context of resilience thinking, wherein adaptive management is a tool in the face of shifting climate regimes and changing landscapes (Holling 1973; Folke et al. 2010). Specifically, the framework provided in this paper is useful to understand some of the underlying social and ecological mechanisms that produce farmer knowledge, and that may in turn inform adaptive management and pathways toward more resilient agriculture (Allen et al. 2011; Carlisle 2014).

In this sense, farmer knowledge represents an untapped source for informing concrete adaptative management techniques that are initially adapted to local contexts but also have the potential to be widely applied. Farmer knowledge provides an *extension* to scientific and policy knowledge bases, in that farmers develop new dimensions of knowledge previously unexplored in the scientific literature. Farmers offer a key source of and process for making abstract knowledge more concrete and better grounded in practice, which is at the heart of adaptive management (Stankey 2005).

Synthesis of key aspects of farmer knowledge

As already elaborated, this framework for farmer knowledge formation offers a useful guide for mapping mechanisms for how farmers learn and codify local knowledge, and also provides necessary groundwork to connect farmer knowledge (in theory) to farm management (in practice). Here, we synthesize six key insights from the study. These key insights in combination with the framework are particularly important to consider when engaging with farmers in alternative agriculture in future studies.

Farmer knowledge is informed by experiential learning

Farmer knowledge accumulation, at least among organic farmers in this study, is mostly observational and experiential. Most farmers considered themselves separate from scientific knowledge production and though scientific knowledge did at times inform their own knowledge production, they still ultimately relied on their own direct observation and personal experiences to inform their knowledge base and make decisions.

This finding underscores the importance of translating theory into practice in alternative agriculture. Without grounding theoretical scientific findings or policy recommendations in practice, whether that be day-to-day practices or long-term management applied, farmers cannot readily incorporate such “outsider” knowledge into their farm operations. Farmers thus provide an important node in the research and policymaking process, whereby they determine if scientific findings or policy recommendations apply to their specific farming context—through direct observation, personal experience, and experimentation.

Farmers engage in scientifically valid knowledge making

Understanding the mechanisms of farmer knowledge formation and precisely how farmers learn is essential to integrating farmer knowledge into the scientific literature. As outlined in the farmer knowledge formation framework, farmer ecological knowledge is accumulated over time based on continuous systematic assessment through direct observation, personal experiences, or experimentation. This iterative feedback approach to learning among organic farmers is akin to the scientific method and parallel in approach to adaptive management in agriculture (Rist et al. 2013).

As highlighted in the results, it is possible for a farmer to acquire expert knowledge within one or two generations of farming alternatively. Documenting this farmer knowledge within the scientific literature—specifically farmer knowledge in the context of relatively new (eg, first- or second- generation) farmers in the US—represents a key way forward for widening agricultural knowledge both in theory and in practice (Carlisle et al. 2019). This finding is significant because it underscores the importance of farmers not as subjects of science but as actors within the scientific community. This study provides one example for documenting farmer knowledge in a particularly unique site for organic agriculture. Future studies may expand on this approach in order to document other contexts with recent but deep agricultural knowledge on alternative farms.

Farmer management is holistic not piecemeal

Farmers tend to think holistically about their farm management. For example, when farmers were asked to talk about soil management specifically, several farmers struggled with this format of question, because they expressed that they do not necessarily think about soil management specifically but tend to manage for multiple aspects of their farm ecosystem simultaneously.

This result aligns with similar findings from Sūmane et al. (2016) across a case study of ten different farming contexts in Europe, and suggests that farmers tend to have a bird’s eye view of their farming systems. Such an approach allows farmers to make connections across diverse and disparate elements of their farm operation and integrate these connections to both widen and deepen their ecological knowledge base.

Maintaining soil structure is at the heart of soil health

For most farmers, maintaining ideal soil structure was the foundation for healthy soil. Farmers emphasized that ideal soil structure was delicately maintained by only working ground at appropriate windows of soil moisture. Determining this window of ideal soil moisture represented a learned skill that each individual farmer developed through the iterative learning process elaborated in Figure 1. This knowledge-making process was informed by both social mechanisms gained through inherited wisdom and informal conversations (in some cases) and ecological mechanisms through direct observation, personal experiences, and experimentation (in a majority of cases). As farmers developed their ecological knowledge of the appropriate windows of soil moisture, their ethos around soil management shifted. In this way, over time (and with a steep learning curve), these farmers learned that no amount of nutrient addition, reduced tillage, cover cropping, or other inputs could make up for damaged soil structure.

Destroying soil structure was relatively easy but had irreversible, long-term consequences and often took years, in some cases even a decade, to rebuild.

This key soil health practice (ie, maintaining soil structure) voiced by a majority of farmers interviewed represented a different framing compared to messaging about soil health vis-a-vis extension institutions (such as the USDA Natural Resources Conservation Service), where soil health principles focus on keeping ground covered, minimizing soil disturbance, maximizing plant diversity, keeping live roots in the soil, and integrating livestock for holistic management. While these five key principles of soil health were mentioned by farmers and were deemed significant, for most farmers interviewed in this study, the foundation and starting point for good soil health was maintaining appropriate soil structure. Though soil structure is clearly important in NRCS conception of soil health, soil structure is not explicitly considered in the core soil health principles.

The results of this study emphasize that the most successful entry point for engaging farmers around soil health is context specific, informed directly by local knowledge. Among farmers in Yolo County—a significant geographic node of the organic farming movement—soil structure is a prevalent concept; however, in another farming context, this entry point may significantly diverge for social, ecological, economic, or other reasons. Each farming context therefore necessitates careful inquiry and direct conversation with local farmers to determine this entry point for engagement on soil health. For this reason, in most cases it may be more relevant to tailor soil health outreach to the local context rather than applying a one-size-fits all model.

Farmer knowledge transfer is critical for agricultural resilience

The capacity to learn and pass on that learning are essential for organic farms to be able to adapt to everchanging social and ecological changes ahead (Sundkvist et al. 2005; Darnhofer et al. 2010). Across all farmers interviewed, including both first- and second-generation farmers, farmers stressed the steep learning curves associated with learning to farm alternatively and/or organically. While these farmers represent a case study for building a successful, organic farm within one (or in a few cases two) generations, the results of this study beg the question: What advancements in farm management and soil management could be possible with multiple generations of farmer knowledge transfer on the same land? Rather than re-learning the ins and outs of farming every generation or two, as new farmers arrive on new land, farmers could have the opportunity to build on existing knowledge from a direct line of farmers before them, and in this way, potentially contribute to breakthroughs in alternative farming. In this sense, moving forward agriculture in the US has a lot to learn from agroecological farming approaches with a deep multi-generational history (Gliessman 2018; Tittonell 2020).

To this end, in most interviews—particularly among older farmers—there was a deep concern over the future of their farm operation beyond their lifetime. Many farmers lamented that no one is slated to take over their farm operation and that all the knowledge they had accumulated would not pass on. There exists a need to fill this gap in knowledge transfer between shifting generations of farmers in order to safeguard farmer knowledge and promote adaptations in alternative agriculture into the future.

Generalizability and scalability of farmer knowledge

Most studies often speak to the scalability of approach or generalizability of the information presented. While aspects of this study are generalizable (eg, farmer knowledge formation presented in Figure 1; working with local extension agents; interview questions applied – see Appendix, Supplement A) particularly to similar farming systems in California such as the Central Coast region, the farmer knowledge presented in this study is not generalizable and not scalable to other regions in the US.

To access farmer knowledge, relationship building with individual farmers leading up to interviews as well as the in-depth interviews themselves require considerable time and energy. While surveys often provide a way to overcome time and budget constraints to learn about farmer knowledge, this study shows that to achieve specificity and depth in analysis of farmer knowledge requires an interactive approach that includes—at a minimum—relationship building, multiple field visits, and in-depth, multi-hour interviews. Accessing farmer knowledge necessitates locally interactive research; this knowledge may not be immediately generalizable or scalable without further locally interactive assessment in other farming regions.

CONCLUSION

Local knowledge among farmers in US alternative agriculture has often been dismissed or overlooked by the scientific community, policymakers, and agricultural industry experts alike; however, this study makes the case for inclusion of farmer knowledge in these arenas. In-depth interviews established that farmers provide an important role in translating theoretical aspects of agricultural knowledge into practice. It is for this reason that farmer knowledge must be understood in the context of working farms and the local landscapes they inhabit.

As one of the first systematic assessments of farmer knowledge of soil management in the US, this research contributes key insights to design future studies on farmer knowledge and farmer knowledge of soil. Specifically, this study suggests that research embedded in local farming communities provides one of the most direct ways to learn about the substance of farmer knowledge; working with the local UCCE advisor in combination with community referrals provided avenues to build rapport and relationships with individual farmers—relationships that were essential to effective research of farmer knowledge.

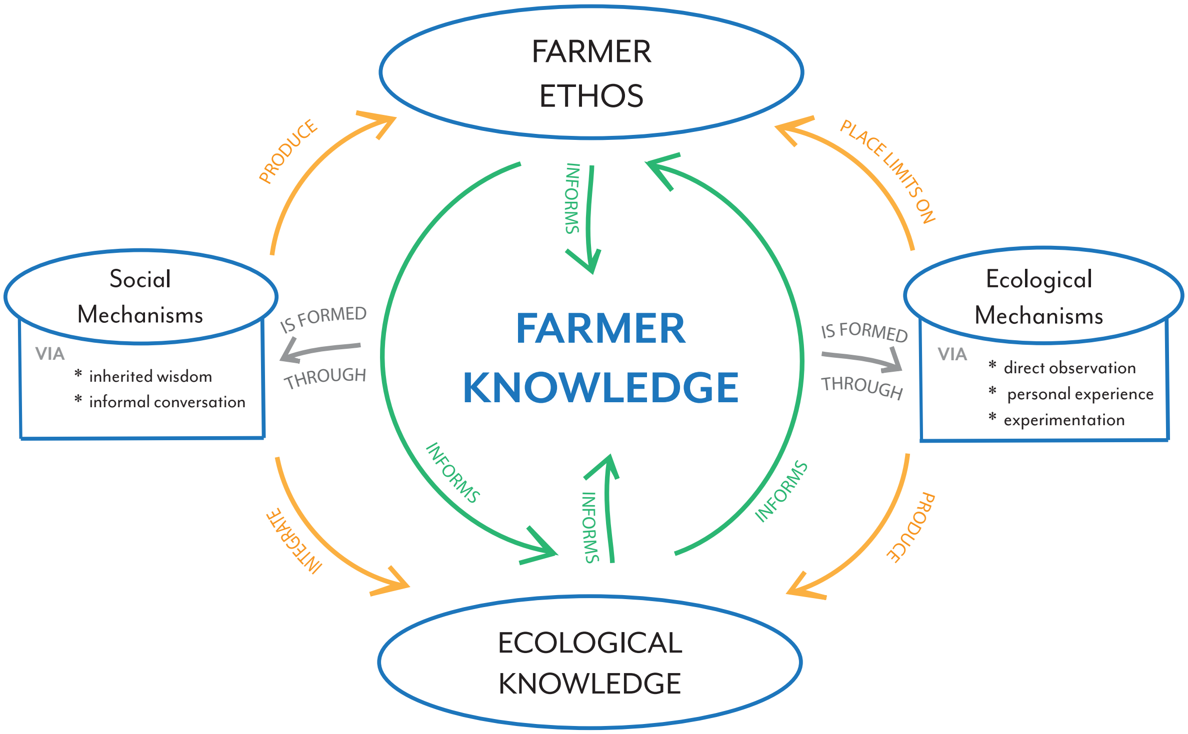
Farmer knowledge of soil management for maintaining healthy soils and productive, resilient agriculture represents an integral knowledge base in need of further scientific research. This study provides a place-based case study as a starting point for documenting this extensive body of knowledge among farmers. It is our hope that this research will inspire future studies on farmer knowledge in other contexts so that research in alternative agriculture can widen its frame to encompass a more complete understanding of farming systems and management motivations—from theory to practice.

ACKNOWLEDGEMENTS

We especially thank the 13 farmers in Yolo County, California for collaborating on this project and sharing their wisdom, time, and personal energy. Sincere thanks to Julie Guthman for inspiring this work and providing guidance.

FIGURES

Figure 1. Farmer knowledge formation: A framework for understanding how the process of farmer knowledge formation occurs.



CHAPTER II

Towards a functional understanding of crop nitrogen availability on working farms: A case study on a community of organic farms in northern California

ABSTRACT

Across agricultural systems, it is currently widespread practice to use measurements of soil inorganic nitrogen (N) as indicators for N availability to crops. Particularly in organic agriculture where N is supplied via organic sources of nitrogen (eg, soil organic matter, cover crops, the integration of crop livestock systems, etc) that are less readily available to crops, a more functional understanding of N availability is important to achieve. In these systems, sufficient availability of N to crops is often dependent on high levels of microbial activity in the soil to process organic N, especially the large reservoir of soil organic N; therefore, indicators for soil organic matter—rather than inorganic N—may serve as a better starting point for pinpointing crop available N. Furthermore, understanding how soil processes that mediate plant and microbial flows of N shift along gradients of soil organic matter could provide insights into soil N cycling, and in turn, crop available N. We focus our study on working organic farms that differ in levels of soil organic matter (SOM)—applied here as a proxy for soil quality—and use these differences in soil organic matter to 1) assess changes in gross N flows (ie, gross mineralization and nitrification rates) across levels of SOM, and 2) quantify the influence of soil edaphic and management factors on soil N processes. Applying a two-step approach, we first developed farm typologies based on soil organic matter data from field surveys; we then determined if N cycling differed among the three farm types assigned. Overall, we found significant differentiation among farms based on soil organic matter levels, strongly driven by both recent management and soil edaphic factors. Our results indicated that soil texture may play a more significant role in determining soil organic matter levels, especially compared to management. However, net and gross N cycling rates did not significantly differ among the farm types defined by indicators for soil organic matter. Still, we did find that indicators for SOM do play a role in influencing N cycling across farm systems studied here. Future research that explores N cycling on working organic farms might focus less on within season dynamics, as gross N flows do not appear to be applicable as soil indicators for N availability, and are less responsive to soil quality and existing management regimes.

INTRODUCTION

A fundamental challenge in agriculture is to limit the environmental impacts of nitrogen losses while still supplying adequate nitrogen to crops and achieving a farm's expected yields (Socolow 1999; Robertson & Vitousek 2009; Möller 2018). To balance among such environmental, ecological, and agronomic demands, it is essential to establish actual availability of nitrogen (N) to crops (Grandy et al. 2022; Drinkwater and Snapp 2007). A holistic, functional understanding of plant N availability is particularly imperative in organic agriculture, as in this farming context, synthetic fertilizers are not applied and instead, production of inorganic N—the dominant form of N available to crops—depends on internal soil processes (Daly et al. 2021). In organic agricultural systems, farmers may seasonally apply cover crops or integrate livestock as alternative sources of nitrogen to crops—in addition to or in place of using organic fertilizers. In applying these alternative sources of nitrogen to soil, organic farmers rely on the activity of soil microbes to transform organic N into inorganic forms of N that are more readily available for crop uptake (Stark et al. 2008).

Currently, the predominant way crop available N is measured in organic agricultural systems tends to examine *pools* of inorganic N in soil (Daly et al. 2021). Inorganic N, or more specifically ammonium (NH_4^+) and nitrate (NO_3^-), represents the predominant forms of N taken up by crop species in ecosystems where N is relatively available, such as in non-organic agricultural systems that apply inorganic fertilizers (Power and Doran 1984). However, in organic systems, crop available N is largely controlled by complex soil processes not adequately captured by simply measuring pools of ammonium and nitrate. First, because nitrogen made available to crops is controlled by soil microbes—wherein crops only have access to inorganic forms of N after microbial N transformations occur to first meet microbial N demand—pinpointing the flow of N moving *through* inorganic N pools as a result of these microbial N transformations is necessary to accurately measure *actual* N availability to crops (Jackson et al. 1989). Second, extensive recycling of N among components of the plant-soil-microbe system complicates relying solely on measurements of inorganic N pools, which do not reflect these dynamics (Paterson 2003; Bowles et al. 2015b; Jilling et al. 2018).

As an example, one previous study in organic vegetable systems showed examples where inorganic N pool sizes in the soil were measured to be low, yet there existed high production and consumption rates of inorganic N (Bowles et al. 2015b). This outcome highlighted that if the turnover of inorganic N is high—for instance, high rates of soil ammonium production (eg, soil N mineralization) exist in the soil with simultaneously high rates of immobilization by soil microbes and high rates of uptake by plants—measured pools of inorganic N may still be low (Burger and Jackson 2003). This study also showed that conversely, there may also exist situations when inorganic N pools are low and rates of ammonium and nitrate production (eg, soil N mineralization and nitrification) are also low, in which case N availability would limit crop production. In organic systems especially, higher carbon (C) availability as a result of organic management can increase these microbially mediated gross N flows, thereby increasing N cycling and turnover of inorganic N (Marriott and Wander 2006). Thus, we hypothesize that measuring total production of ammonium from organic N, or gross N mineralization, and subsequent total production of nitrate from ammonium, or gross N nitrification, may provide a more complete characterization of crop available N in the context of organic systems (Burger and Jackson 2003).

Though the application of such diverse management practices on organic farms is known to affect rates of N cycling in soil (Bowles et al. 2014), measuring N flow rates as a proxy for crop available N is currently uncommon on working organic farms. The current historical emphasis on measuring inorganic pools of N in organic agriculture was originally imported from non-organic farming, wherein the Sprengel-Liebig Law of the Minimum was a widely accepted agronomic principle (Heckman 2006). In practice, this Law of the Minimum placed particular importance on using artificial fertilizers to overcome so-called "limiting" nutrients—namely, inorganic forms of N. Because inorganic N is relatively straightforward to measure, focus on quantifying pools of inorganic N has since become common practice among agronomists and agricultural researchers (van der Ploeg et al. 1999; Robertson 1997; Heckman 2006).

However, the continued acceptance of the Law of the Minimum in organic agriculture underscores the gap in a *functional* understanding of organic agricultural systems, in particular the role of soil microbes in mediating N cycling. To understand crop available N more holistically, there is a need to measure actual flow rates of soil N—*in addition to*—static pools of inorganic N (Murphy et al. 2003; Hart et al. 1994; Kaye and Hart 1997). Soil indicators that adequately capture N availability to crops are therefore necessary to move beyond the legacy of the Law of the Minimum in organic agriculture. Unpacking the soil processes that mediate flows of N may ultimately provide a more accurate characterization of soil N cycling and in turn, N availability to crops.

Unfortunately, gross N mineralization and nitrification rates are very difficult to measure in practice, particularly on working organic farms (Murphy et al. 2003; Barrett and Burke 2000). While net N flows (ie, net mineralization and nitrification rates) are easier to measure in comparison to gross N flows and can provide a useful measure of N cycling dynamics as a complement to measurements of inorganic N pools, net N flows still pose serious limitations—namely that net rates cannot detect plant-soil-microbe interactions and therefore are not adequate as metrics for determining crop available N (Davidson et al. 1991; Schimel 2004). In particular, relying on net N flows as a measure of N availability does not account for the ability of plants to compete for inorganic N, and assumes plants take up inorganic N only after microbial N demands are satisfied (Zhu et al. 2017).

It is also possible that measuring soil organic matter pools could help indicate N availability because SOM supports microbial abundance and activity, and because SOM is also the source of substrates for N mineralization (Jarvis et al. 1996; van Wesemael et al. 2019). Several studies have proposed measuring soil organic matter (SOM) levels to complement measuring inorganic N pools, understand soil N cycling, and infer N availability (Drinkwater & Snapp 2007, Jilling et al. 2018). Assessing the total quantity of organic carbon and nitrogen within soil organic matter represents one established method for measuring levels of soil organic matter, and is more readily measurable than gross N rates. Additional indicators for quantifying "labile" pools of organic matter, such as POXC (Permanganate-OXidizable Carbon) and soil protein, have also become more widely studied in recent years, and applied on organic farms as well (Sprunger et. 2021; Hurisso and Culman 2021; Lucas and Weil 2012).

When used in combination with more established soil indicators that measure organic C and N pools (eg, total organic C and total soil N), this suite of indicators may potentially provide added insight to understanding crop available N (Osterholz et al. 2017; Lucas and Weil 2021). Importantly, applied together these four indicators for soil organic matter levels may also more readily and accurately serve as a proxy for soil quality—generally defined as a soil's ability to perform essential ecological functions key to sustaining a farm operation (Doran and Parkin 1994). Despite the availability of these soil indicators, very few studies have systematically examined the way in which SOM levels on working farms compare to N cycling processes, and specifically how SOM levels compare to microbially mediated gross N rates.

Further, it is still unclear to what degree the interactions between soil edaphic characteristics and soil management influence N cycling and N availability to crops (Osterholz et al. 2018; Laine et al. 2018). For instance, soil texture (eg, % sand or % clay) may play a mediating role in N cycling, where soils high in clay content may limit substrate availability as well as access to oxygen, which in turn, may restrict the efficiency of N cycling (Cookson and Murphy 2004; Laine et al. 2018). In this sense, it is important to understand the role that soil edaphic characteristics (eg, soil texture class, soil pH, etc) play in order to identify the underlying baseline limits imposed by the soil itself. Equally important to consider is the role of soil management in mediating N cycling.

Compared to controlled experiments, soil management regimes on working farms can be more complex and nonlinear in nature due to multiple interacting practices (eg, crop diversity, crop rotation, cover crop application, tillage, irrigation, etc) applied over the span of several years, and even multiple decades. To date, a handful of studies conducted on working farms have examined tradeoffs among different management systems (Jackson et al. 2004, Williams et al. 2020), though few such studies examine the cumulative effects of multiple management practices across a gradient of working organic farms. However, understanding the cumulative effects of management practices is key to link soil management to N cycling on working farms (Hu et al. 2021). Likewise, it is important to examine the ways in which local soil edaphic characteristics may limit farmers' ability to improve soil quality through management practices.

Though underutilized in this context, the development of farm typologies presents a useful approach to quantitatively integrate the heterogeneity in management on working organic farms (Pacini et al. 2014). Broadly, typologies allow for the categorization of different types of organic agriculture and provide a way to synthesize the complexity of agricultural systems (Kostrowicki 1977). Previous studies that make use of farm typologies (Bowles et al. 2015b, see Figure 8; Marriott and Wander 2006) found that differences in total soil N across farms are largely defined by levels of soil organic matter. Extending existing studies, in this study we aim to answer the following questions—

1. Are there measurable differences among working organic farms based on soil indicators linked to soil quality? To what extent do management practices and/or soil texture play a role in explaining these differences?
2. If so, to what extent do these soil indicators linked to soil quality influence differences in N cycling?
3. How do soil indicators linked to soil quality, management practices, and soil texture interact to predict gross N cycling rates on working farms?

To address these questions, we conducted field research at 27 farm field sites in Yolo County, California, USA, and used four commonly available indicators of soil organic matter to classify farm field sites into farm types *via* k-means cluster analysis. Using farm typologies identified, we examined the extent to which soil texture and/or soil management practices influenced these measured soil indicators across all working organic farms, using Linear Discriminant Analysis (LDA) and Variation Partitioning Analysis (VPA). We then determined the extent to which gross N cycling rates and other soil N indicators differed across these farm types. Lastly, we developed a linear mixed model to understand the key factors most useful for predicting potential gross N cycling rates along a continuous gradient, incorporating soil indicators, on-farm management practices, and soil texture data. Our study highlights the usefulness of soil indicators towards understanding plant-soil-microbe dynamics that underpin crop N availability on working organic farms. While we found measurable differences among farms based on soil organic matter, strongly influenced by soil texture and management, these differences did not translate for N cycling indicators measured here. Though N cycling is strongly linked to soil organic matter, indicators for soil organic matter are not strong predictors of N cycling rates.

METHODS

Study site

We conducted our experiment on 13 farms and 1 research station in Yolo County, California in June 2019 (for the initial field visit) and in mid- to late-July 2019 (for field sampling). We sampled two fields at each farm and a single treatment at the research station, for a total of 27 field sites. This region, located along the western side of the Sacramento Valley, is characterized by a Mediterranean-type climate with cool, wet winters and hot, dry summers (Jackson et al. 2011). Precipitation in the 2019 water year 2019 was 807 mm—the fifth wettest winter (2018/2019) on record. The mean maximum and minimum temperatures were 33.9^{o}C and 15.5^{o}C, respectively for July 2019. Mean annual maximum and minimum temperatures for 2019 were 24^{o}C and 9.8^{o}C, respectively.

All farm sites were on similar parent material (mixed alluvium derived from sandstone and shale) according to soil survey data (Soil Survey Geography, SSURGO, parent material data). All fields had soil textural class that was either loam, clay loam, or silty clay loam, based on soil texture analyses.

To identify potential participants for this study, we first consulted the USDA Organic Integrity database and assembled a comprehensive list of all organic farms in Yolo County (N=114). Next, with input from the University of California Cooperative Extension (UCCE) Small Farms Advisor (eg, local Cooperative Extension agent) for Yolo County, we narrowed the list of potential farms by applying several criteria for this study: 1) grow fruit, vegetables, and other diversified crops; 2) located within Yolo County; 3) at least 10 years of experience in organic farming; 4) at least five years of farming on the same land. This significantly reduced the pool of potential participants to 16 possible farms. In the end, 13 organic farms and 1 local research station agreed to an initial field interview in early summer 2019 (IRB ID:2018-04-11014) and field sampling in mid-summer 2019. Farmers who agreed to participate were not asked to change their management or planting plans.

Soil Sampling

During the initial field visits in June 2019, two field sites were selected in collaboration with farmers on each participating farm; these sites represented fields in which farmers planned to grow summer vegetables. Therefore, only fields with all summer vegetable row crops (eg, no fields with cover crops or fallow fields) were selected for sampling. At this time, farmers also discussed management practices applied for each field site, including information about crop history and rotations, bed prepping if applicable, tillage, organic fertilizer input, and irrigation (see Appendix, Supplement B). Because of the uniformity of long-term management at the field station (see UC Davis Russell Ranch Sustainable Agriculture Facility's Century Experiment; Wolf et al. 2017, Figure 1), only one treatment was selected in collaboration with the Cropping Systems Manager—a tomato field in the organic corn-tomato-cover crop system.

Since the farms involved in this study generally grew a wide range of vegetable crops, we designed soil sampling to have greater inference space than a single crop, even at the expense of adding variability. Sampling was therefore designed to capture indicators of nitrogen cycling rates and nitrogen pools in the bulk soil at a single timepoint. Fields were sampled mid-season near peak vegetative growth when crop nitrogen demand is the highest. Using the planting date and anticipated harvest date for each crop, peak vegetative growth was estimated and used to determine timing of sampling. We collected bulk soil samples (ie, not directly in dense root zones) that we did not expect to be strongly influenced by the particular crop present. This sampling approach provided a snapshot of on-farm nitrogen cycling.

Field sampling occurred over the course of four weeks in July 2019. To sample each site, a random 10m by 20m transect area was placed on the field site across three rows of the same crop, away from field edges. Within the transect area, three composite samples each based on 5 sub-samples were collected approximately 30cm from a plant at a depth of 20cm using an auger (see Appendix, Figure S1). Subsamples (500g fresh weight soil) were composited on site, and mixed thoroughly by hand for 5 minutes before being placed on ice and immediately transported back to the laboratory. To determine bulk density (BD), we hammered a steel bulk density core sampler approximately 30cm from a plant at a depth 20cm below the soil surface and recorded the dry weight of this volume to calculate BD; we sampled three replicates per site and averaged these values to calculate final BD measurements for each site.

Laboratory Processing

Soil samples were preserved on ice until processed within several hours of field extraction. Each sample was sieved to 4mm and then either air dried, extracted with 0.5M K_2SO_4, or utilized to measure net and gross N mineralization and nitrification (see below). Air dried samples were measured for gravimetric water content (GWC) and BD. Gravimetric water content was determined by drying fresh soils samples at 105°C for 48 hrs. Moist soils were immediately extracted and analyzed colorimetrically for NH_4^+ and NO_3^- concentrations (detection limit of approximately 0.001 ppm N) using modified methods from Miranda et al. (2001) and Forster (1995). Additional volume (50 mL) of extracted samples were subsequently frozen for future laboratory analyses.

To determine soil textural class, air dried samples were sieved to 2mm and subsequently prepared for analysis using the “micropipette” method (Miller & Miller 1987). Water holding capacity (WHC) was determined using the funnel method, adapted from Geisseler et al. (2009), where a jumbo cotton ball thoroughly wetted with deionized water was placed inside the base of a funnel with 100g soil on top. Deionized water was added and allowed to imbibe into the soil until no water dripped from the funnel. The soil was allowed to drain overnight (covered with parafilm). A subsample of this soil was then weighed and dried for 48 hours at 105°C. The difference following draining and oven drying of a subsample was defined as 100% WHC.

Air dried samples were sieved to 2mm, ground, and then analyzed for total soil N and total organic C using an elemental analyzer (varioMax cute Elemental Analyzer; detection limit of approximately 0.01 μg-C/g soil and 0.01 μg-N/g soil for total C and N, respectively) at the Ohio State Soil Fertility Lab (OSU, Ohio, USA); additional soil data including pH and soil protein were also measured at this lab. Soil protein was determined using the autoclaved citrate extractable soil protein method outlined by Hurisso et al. (2018). Additional air-dried samples were sieved to 2mm, ground, and then analyzed for POXC using the active carbon method described by Weil et al. (2003), but with modifications as described by Culman et al. (2012). In brief, 2.5g of air-dried soil was placed in a 50mL centrifuge tube with 20mL of 0.02 mol/L $KMnO_4$ solution, shaken on a reciprocal shaker for exactly 2 minutes, and then allowed to settle for 10 minutes. A 0.5-mL aliquot of supernatant was added to a second centrifuge tube containing 49.5mL of water for a 1:100 dilution and analyzed at 550 nm. The amount of POXC (mg-C/kg air-dried soil) was determined by the loss of permanganate due to C oxidation (Hurisso et al. 2016).

Net mineralization and nitrification

To measure net N mineralization and nitrification in soil samples, fresh soil subsamples were incubated in 50mL falcon tubes using a parafilm cover, applying methods adapted from Wade et al. (2016). Prior to incubation, each subsample was weighed to 7g and adjusted to 60% water holding capacity. Each sample had three parallel sets of subsamples for each incubation period (t = 1, 28, and 54 d). At the end of each incubation period, soil samples were extracted with 0.5M K2SO4, placed on the shaker for 30 minutes, centrifuged for 3 minutes at 7500 rpm, and then filtered using Whatman #42 filter paper. Standard colorimetry (as described in section above) was used to measure NH_4^+ and NO_3^- concentrations for each sample at each time point. Net N mineralization and nitrification were calculated as the cumulative change in inorganic N (NH_4^+ and NO_3^-) between a given sampling date (*t*) and the initial inorganic N levels (t = 1 d). In the results, we report sampling date at t = 28 days.

Gross mineralization and nitrification

To measure gross N mineralization and nitrification in soil samples, we applied an isotope pool dilution (IPD) approach, adapted from Braun et al. (2018). This method is based on three underlying assumptions listed by Kirkham & Bartholomew (1954): 1) microorganisms in soil do not discriminate between ^{15}N and ^{14}N; 2) rates of processes measured remain constant over the incubation period; and 3) ^{15}N assimilated during the incubation period is not remineralized.

To prepare soil samples for IPD, we adjusted soils to approximately 40% WHC prior to incubation with deionized water. Next, four sets of 40g of fresh soil *per* subsample were weighed into specimen cups and covered with parafilm. Based on initial NH_4^+ and NO_3^- concentrations determined above, a maximum of 20% of the initial NH_4^+ and NO_3^- concentrations (for N mineralization and N nitrification, respectively) was added as either $^{15}N\text{-}NH_4^+$ or $^{15}N\text{-}NO_3^-$ tracer solution at 10 atom%; the tracer solution also raised each subsample soil water content to 60% WHC. This approach increased the production pool as little as possible (thus avoiding stimulation of microbial NH_4^+ immobilization processes) while also ensuring sufficient enrichment of the NH_4^+ and NO_3^- pools with $^{15}N\text{-}NH_4^+$ and $^{15}N\text{-}NO_3$, respectively, to facilitate high measurement precision (Davidson et al. 1991, Di et al. 2000). Due to significant variability of initial NH_4^+ and NO_3^- pool sizes in each soil sample, differing amounts of tracer solution (to achieve an optimum level of ^{15}N tracer and uniform soil water content at 60% WHC) were added to each sample set evenly across the soil surface. To begin the incubation, each of the four subsamples received the tracer solution via evenly distributed circular drops from a micropipette. The specimen cups were placed in a dark incubation chamber at 20°C.

After four hours (T_1), two subsample incubations (one for N mineralization and one for N nitrification) were stopped by extraction with 0.5M K_2SO_4 as above for initial NH_4^+ and NO_3^- concentrations. Filters were pre-rinsed with 0.5 M K_2SO_4 and deionized water and dried in a drying oven at 60°C to avoid the variable NH_4^+ contamination from the filter paper. Soil extracts were frozen at -20°C until further isotopic analysis. Similarly after 24 hrs (T_2), two subsample incubations (one for N mineralization and one for N nitrification) were stopped by extraction as previously detailed, and subsequently frozen at -20°C.

At a later date, filtered extracts were defrosted, homogenized, and analyzed for isotopic composition of NH_4^+ and NO_3^- in order to calculate gross production and consumption rates for N mineralization and nitrification. We prepared extracts for isotope ratio mass spectrometry using a microdiffusion approach based on Lachouani et al. (2010). Briefly, to determine NH_4^+ pools, 10mL aliquots of samples were diffused with 100mg magnesium oxide (MgO) into Teflon coated acid traps for 48 hours on an orbital shaker. The traps were subsequently dried, spiked with 20µg NH4$^+$-N at natural abundance to achieve optimal detection, and subjected to EA-IRMS for ^{15}N:^{14}N analysis of NH_4^+. Similarly, to determine NO_3^- pools, 10mL aliquots of samples were diffused with 100mg magnesium oxide (MgO) into Teflon coated acid traps for 48 hours on an orbital shaker. After 48 hours, acid traps were removed and discarded, and then each sample diffused again with 50mg Devarda's alloy into Teflon coated acid trap for 48 hours on an orbital shaker. These traps were dried and subjected to EA-IRMS (UC Davis Stable Isotope Facility) for ^{15}N:^{14}N analysis of NO_3^+. Twelve dried samples with very low (<10 µg NO_3-N) spiked with 20µg NH4$^+$-N at natural abundance to achieve optimal detection.

Gross production and consumption rates for mineralization and nitrification were calculated based on atom percent excess (APE) values calculated for each pool as atom% ^{15}N of the sample minus the natural ^{15}N abundance of the sample, and then APE divided by 100 and multiplied by the initial pool size. This approach assumed that the recovery rate of the added ^{15}N for all N pools as the total amount of ^{15}N recovered divided by the amount added (Hart et al. 1994). Gross NH_4^+ and NO_3^- production (GP; Equation A) and gross NH_4^+ and NO_3^- consumption (GC; Equation B) were calculated for samples following Kirkham and Bartholomew (1954)—

$$\mathrm{GP} = \frac{C_{t2}-C_{t1}}{t_2-t_1} \times \left(\frac{\ln\left(\frac{APE_{t1}}{APE_{t2}}\right)}{\ln\left(\frac{C_{t2}}{C_{t1}}\right)} \right) \qquad \text{(A)}$$

$$\mathrm{GC} = \frac{C_{t1}-C_{t2}}{t_2-t_1} \times \left(1 + \frac{\ln\left(\frac{APE_{t2}}{APE_{t1}}\right)}{\ln\left(\frac{C_{t2}}{C_{t1}}\right)} \right) \qquad \text{(B)}$$

where t_1 and t_2 represent incubation stop times, C_{t1} and C_{t2} represent soil NH_4^+ (or NO_3^-) concentrations (µg-N/g soil), and APE is ^{15}N atom% excess.

Soil Management

In addition to the soil biogeochemical variables described above, farmers were also interviewed to determine specific soil management practices on their farms. Farmers were asked to describe the number of tillage passes they performed per field per season; the total number of crops per acre that the farm produced during one calendar year at the whole farm level; the degree to which the farm utilized integrated crop and livestock systems (ICLS) on the farm; crop rotational complexity for each field; and the frequency of cover crop plantings for each field. To calculate the frequency of tillage, we tallied the total number of tillage passes per season for each field. To calculate crop abundance, the total number of crops (at the species level) grown per year at the whole farm level was divided by the total acreage farmed. To capture the use of ICLS, we created an index based on the number of and type of animals utilized. Specifically, the index was calculated by first adding the number of animals used in rotation on farm for each animal type (eg, chickens, cows, pigs, sheep, etc) and then dividing by the total number of acres for each farm. These raw values were then normalized, creating an index range from 0 (no integration of crop-livestock livestock systems) to 1 (high integration of crop-livestock systems). Lastly, to quantify crop rotational complexity, a rotational complexity index (RCI) was calculated for each site using the formula outlined by Socolar et al. (2021). Cover crop frequency was determined using the average number of cover crop plantings per year, calculated as cover crop planting counts over the course of two growing years for each field site.

Statistical Analyses

Several multivariate techniques were implemented in order to group, visualize, and explore differences across the farm field sites based on soil indicators, soil nitrogen cycling, soil texture class (as a proxy for soil edaphic characteristics), and soil management data. All data was standardized to normal distribution ($\mu = 0$ and $\sigma = 1$).

Cluster analysis: Identifying and characterizing farm types

In order to identify farm typologies based on indicators for soil organic matter levels, we first used several clustering algorithms. First, a k-means cluster analysis based on four key soil indicators—soil organic matter (total C and POXC), total soil nitrogen, and available nitrogen (soil protein)—was used to generate three clusters of farm groups using the facoextra and cluster (version 4.2.1) packages in R (R Core Team, 2022). The cluster analysis results were divisive, non-hierarchical, and based on Euclidian distance, which calculates the straight-line distance between the soil indicator combinations of every farm site in Cartesian space (n- site dimensions), and created a matrix of these distances (Borcard et al. 2011). To determine the appropriate number of clusters for the cluster analysis, a scree plot was used to signal the point at which the total within-cluster sum of squares decreased as a function of the increasing cluster size. The location of the kink in the curve of this scree plot delineated the optimal number of clusters, in this case three clusters (Hahs-Vaughn 2016).

To further explore appropriate cluster size, we used a histogram to determine the structure and spread of data among clusters. A Euclidean-based dendrogram analysis was then used to further validate the results of the cluster analysis. In addition to confirming the results of the cluster analysis, the dendrogram plot showed relationships between sites and relatedness across all sites. To visual cluster analysis results, the final three clusters were plotted based on the axes produced by the cluster analysis.

One drawback of cluster analyses is that there is no measure of whether the groups identified are the most effective combination to explain clusters produced by soil indicators, or whether they are statistically different from one another. To address this gap, we used ANOSIM (Analysis of Similarities) to evaluate and compare the differences between clusters identified with the cluster analysis above. We calculated the global similarity in addition to pairwise tests of each cluster.

To formally establish the three farm types and also make the functional link between organic matter and management explicit, we used the three clusters that emerged from the k-means cluster analysis based on soil organic matter indicators, and explored differences in management approaches among the clusters. We then created three farm types based on this exploratory analysis. Specifically, we first analyzed management practices among sites within each cluster to determine if similarities in management approaches emerged for each cluster. Based on this analysis, we used the three clusters (Cluster I, II, III) from the cluster analysis to create three farm types (Farm Type I, II, III) categorized by soil organic matter levels and informed by management practices applied.

LDA and VPA: Understanding the role of management and soil edaphic characteristics

Using the three farm types from above, we then analyzed whether our classification created strong differences along soil texture and management gradients using a linear discriminant analysis (LDA). LDA is most frequently used as a pattern recognition technique; because LDA is a supervised classification, class membership must be known prior to analysis (Vandeginste et al. 1998). The analysis tests the within group covariance matrix of standardized variables and generates a probability of each farm sites being categorized in the most appropriate group based on these variable matrices (Qiao et al. 2009).

To characterize soil texture, we used soil texture class (% sand, % clay). To characterize soil management, we used crop abundance, tillage frequency, and crop rotational complexity—the three management variables with the strongest gradient of difference among the three farm types. A confusion matrix was first applied to determine if farm sites were correctly categorized among the three clusters created by the cluster analysis. Additional indicator statistics (eg, percentage of sensitivity, accuracy, and positive predicted values) were also generated to confirm if the LDA was sensitive to input variables provided. A plot with axis loadings is provided to visualize the results of the LDA and display differences across farm groups visually. The LDA was carried out using the MASS (Version 4.1.7; Venables and Ripley 2002) R package.

To build on the results of the LDA, we performed a variation partitioning analysis (VPA) to determine the level of variation in soil organic matter indicators explained by the soil texture variables, soil management variables, and their interactions (Li et al. 2021). VPA was performed using the vegan package in R (Version 4.2.1).

ANOVA and LMM: Comparing N cycling to SOM, management, and soil texture

To visualize soil nitrogen cycling variables based on farm types produced by the cluster analysis, we created a series of side-by-side box plots using the ggplot2 package in R (Version 4.1.7). Differences across farm types were assessed for each variable using one-way analysis of variance (ANOVA; R Core Team, 2022). To analyze the global effect of soil nitrogen and carbon, soil texture class, and on-farm management covariates on gross N cycling rates, we developed a linear mixed model (LMM) or mixed-effects model, using the lme4 and lmerTest packages in R (Version 4.2.4), a method commonly applied in similar studies (Suuster et al. 2012; Guzman et al. 2021). Briefly, a linear mixed model can be defined as—

$$\hat{y} = \alpha + \beta X + \gamma^{SITE} + \varepsilon$$

where $\hat{y}$ is the response attribute of the mixed mode in column vector form; α is the intercept; slope β is a column vector and represents the fixed effects regression coefficients; X is a matrix of independent predictor variables; γ^{SITE} is the random site effect; and ε is the error term of residuals (Bates et al. 2010). To build the linear mixed models, we used 10 covariates that included soil nitrogen and carbon indicators (soil nitrogen and ammonium concentrations), five key management variables described above, and soil texture variables (% sand, % clay). To limit effects of collinearity among soil organic matter indicators, we used Dimension 1, derived from the results of the k-means cluster analysis, as a final covariate to indicate soil organic matter quality.

For each model selection (ie, Model 1: Gross ammonification rates; Model 2: Gross nitrification rates), we assessed fixed covariates with a tiered stepwise function (Jamil et al. 2012). Prior to assessment all covariates were normalized ($\mu = 1$, $\sigma = 0$). We then used a forward and backward tiered stepwise model simplification in order to reduce model complexity and to determine interactives effects. To do so, we applied the Akaike Information Criteria (AIC, Akaike 1973) to assess quality of model fit using the step() function in R (Version 2.1.4; Burnham and Anderson 1998). In addition to running stepwise test models with all covariates, we conducted null models in which no covariates were used (Jamil et al. 2012; Burnham and Anderson 1998).

Using the lmer() function (R, Version 2.1.4) for each case, we ran the final mixed model with corresponding covariates that considered fixed and random effects for each site (1 | site) (R, Version 2.1.4). P-values are provided based on comparing models with an analysis of variance for the likelihood ratio test of the final model against the null model. Final models were assessed for multicollinearity using generalized variance inflation factors (GVIFs, Zuur et al. 2009), which never breached a threshold of 10. A straight line for quantile-quantile (QQ) plots of linear model residuals and random effect means confirmed normality for final models (Harrison et al. 2018).

RESULTS

The 27 farm field sites had a range of crops planted for the 2019 late spring-summer planting season (Table 1). Soil textural class ranged from loam to silty clay loam to clay loam across all 27 field sites (Table 1). Soil sand content, clay content, and pH for each site are also listed in Table 1. Table 2 summarizes indicators for soil organic matter at each field site, and Table 3 lists values for key N cycling indicators across all field sites. Lastly, Table 4 summarizes soil management practices for all field sites, including metrics for crop rotational complexity, tillage frequency, use of ICLS, crop abundance, and the rate of cover crop application.

Cluster analysis: Identifying and characterizing farm types

Using indicator variables for soil organic matter levels, we performed a k-means cluster analysis (Figure 1) to develop a meaningful classification of farms. Scree plot results indicated that three clusters produced the most consistent separation of field sites. As shown in Figure 1, the two-dimensional cluster analysis produced a strong first dimension (Dimension 1), which explained 86.7% of the separation among the 27 field sites. Total N, total C, POXC, and soil protein variables strongly explained this separation of farm types, as shown by the lack of overlap among the clusters along the Dimension 1 axis. Histogram results (see Appendix, Figure S2) provide a visual summary of linear difference among the three clusters and further confirms minimal overlap among clusters; however, Cluster I and Cluster II fields showed low dissimilarity between values 0 and -2 (see Appendix, Figure S2). Results from the average distance-based linkages of the dendrogram analysis (see Appendix, Figure S3) similarly further established the accuracy of field site groupings determined by the cluster analysis. These results indicated that Cluster II sites were more closely related to Cluster III sites compared to Cluster I sites (see Appendix, Figure S3).

ANOSIM showed strongly significant ($p = 0.001$) global differences among the three clusters ($R = 0.785$), where a value of 1 delineates 0% overlap between clusters. Overall, ANOSIM verified the farm types obtained from the cluster analysis. In addition, ANOSIM pairwise t-tests that compared each individual cluster in pairs (Table 5) confirmed strongly significant dissimilarities between Cluster I and Cluster III sites ($R = 0.982$, $p = 0.001$). ANOSIM pairwise t-tests also indicated that Cluster I sites were significantly ($p = 0.01$) divergent from Cluster II sites; however, Cluster I and Cluster II showed less dissimilarities ($R = 0.583$) than Cluster II and Cluster III sites ($R = 0.766$, $p = 0.001$). ANOSIM pairwise t-test results were in congruence with the results provided by the histogram (see Appendix, Figure S2).

Classification of farm sites using k-means clustering (Cluster I, II, and III) closely matched differences in on-farm management approaches (Farm Type I, II, and III, respectively). It is important to note that while general trends between clusters and management emerged, the management practices analyzed here do not fully encompass the management regimes of each farm field site, and are intended to be exploratory rather than definitive. Several general trends emerged across the three farm types (Table 6). For instance, Farm Type I, comprised of six field sites, consisted of fields with higher crop abundance values and fields that more frequently planted cover crops compared to Farm Type III. These sites used lower impact machines (eg, machines weighing less than 1,800 lbs) and applied a lower number of tillage passes (<5 passes) compared to Farm Type II and III. In contrast, Farm Type II, also comprised of six field sites, and Farm Type III, comprised of fifteen field sites, represented fields on the lower end of crop abundance values and sites that applied cover crop plantings at a lower frequency than Farm Type I. Farm Type III on average applied a higher number of tillage passes and on average were on the lower end of ICLS index compared to both Farm Type I and Farm Type II. In general, Farm Type II used management approaches that frequently overlapped with Farm Type III, and less frequently overlapped with Farm Type I.

Overall, farm types significantly differentiated based on indicators for soil organic matter levels (Figure 2). For all four indicators displayed in Figure 2, differences among the three farm types were highly significant ($p < 0.001$). As visualized in the side-by-side box plot comparisons for all four indicators for soil organic matter levels, Farm Type I consistently showed the highest mean values across all four indicators, while Farm Type III consistently showed the lowest mean values across all four indicators. Farm Type I had mean values of 0.21 mg-N kg-soil^{-1} for total soil N, 2.3 mg-C kg-soil^{-1} for total organic C, 787 mg-C kg-soil^{-1} for POXC, and 7.4 g g-soil^{-1} for soil protein; compared to Farm Type I, Farm Type III had means values 43% lower for total soil N, 48% lower for total organic C, 58% for POXC, and 66% lower for soil protein. Compared to Farm Type I, Farm Type II had mean values 38% lower for total soil N, 26% lower for total organic C, 28% lower for POXC, and 30% lower for soil protein than Farm Type I. Standard errors for all four indicators are shown in Figure 2.

LDA and VPA: Understanding the role of management and soil texture

Results of the LDA showed that both linear discriminant factors (LD1, LD2) are most strongly explained by soil texture (eg, % sand; % clay), as shown by the LDA loadings (Table 7). Management practices (eg, tillage frequency, crop abundance, and crop rotational complexity) all equally, but weakly, influenced LD1 and LD2 (Table 7). LD1, which explained 66.3% of the variance, was effective at separating the Farm Type I and Farm Type III (Figure 4). However, Farm Type II overlapped with both Farm Type I and Farm Type III for LD1. In contrast, LD2, which explained 33.6% of the variance, did not display a definitive separation between the Farm Type I and Farm Type III; however, LD2 was effective at separating Farm Type II from Farm Type I and Farm Type III.

LDA accurately discriminated between the three farm types, with an overall accuracy of 90.1% ($p < 0.001$), as shown in Table 8. Model accuracy was high for all three farm types (>80%). The model had the greatest sensitivity to Farm Type II and Farm Type III (>80%), and low sensitivity to Farm Type I (< 80%) (Table 8). Both Farm Type I and Farm Type III displayed minimal confusion with Farm Type II, as the comparison of training and validation data details (Table 9).

We determined the proportion of variation in the three farm types accounted for by management and by soil texture (Figure 5). Soil textural class (which included % sand, % clay predictors) contributed 28% of unique variation ($p < 0.001$), while management (which included crop abundance, tillage, and crop rotational complexity as predictors) contributed 18% of unique variation ($p < 0.01$). The shared contribution for all predictors was 1%, and the overall contribution of all predictors was 47%.

ANOVA and LMM: Comparing N cycling to SOM, management, and soil texture

We found across all 27 farm sites sampled that gross N mineralization rates ranged from 0.05 – 4.82 μg-NH4$^+$-N g-soil^{-1} day^{-1} and gross N nitrification rates ranged from 0.55 – 5.90 μg-NO3$^-$-N g-soil^{-1} day^{-1}. We determined net N mineralization rates ranged from 0.07 – 1.51 μg-NH4$^+$-N g-soil^{-1} day^{-1}, while net N nitrification rates had a wider range from 1.53 – 25.18 μg-NO3$^-$-N g-soil^{-1} day^{-1}. We visually compare the six key N cycling variables—pools of inorganic N (eg, soil ammonium and nitrate concentrations), and net (eg, net mineralization and nitrification) and gross N (eg, gross mineralization and nitrification) rates—across the three farm types (Figure 3). Despite the variation in net and gross N mineralization and nitrification rates, using the farm types developed above, we found that N cycling variables were not significantly different across the three farm types for all six variables examined—based on ANOVA results (Figure 3).

Given the variation in gross N rates reported above, we further explored the drivers of this variation in gross N rates using mixed modelling approaches. Table 10 shows results provide for the linear mixed models used for the prediction of potential gross ammonification rates (Model 1). Soil ammonium (NH_4^+) concentration and % sand were significant predictors ($p= 0.001$, $p= 0.01$, respectively) of gross mineralization rates. While not significant, indicators for SOM (ie, Dimension 1 from the cluster analysis) were selected and also included in the model, based on AIC results. We also provide results from the selected linear mixed model used for prediction of potential gross nitrification rates (Model 2) in Table 11. As shown, indicators for SOM emerged as the sole significant covariate ($p = 0.01$). While not significant, crop abundance was also selected and included in the model, as determined by AIC results.

DISCUSSION

This on-farm study found significant differentiation among the organic farm field sites sampled based on soil organic matter levels—and created a gradient in soil quality among the three farm types. While we found that differences in soil quality were generally aligned with trends in management among sites, soil texture—rather than management—emerged as the stronger driver of soil quality. Though initially, we found that net and gross N cycling rates were not significantly different across farm types, gross N cycling rates showed considerable variation among farm types. To determine drivers of this variation, we explored key predictors for soil N cycling and found that SOM indicators influenced gross N mineralization and nitrification rates, in particular gross nitrification rates.

Links between soil organic matter and on-farm management

Each of the four indicators for soil organic matter used in this study—total soil N, total organic C, POXC, and soil protein—showed a strong correlation with farm type, and collectively, created a gradient in soil quality (Figure 2). Farm Type I consistently showed the highest values for total soil N, total organic C, POXC, and soil protein, which suggests sites in this farm type had higher soil quality compared to Farm Type II and III; similarly, Farm Type II consistently showed intermediate values for all four indicators for soil organic matter. Lastly, Farm Type III consistently showed the lowest values across all four indicators, which suggests sites in this latter farm type had lower soil quality compared to the other two farm types. These initial results highlight the usefulness of establishing farm typologies based on indicators for soil organic matter as a novel approach to study gradients in soil quality on organic farms. The three farm types generated based on soil organic matter levels served as a key starting point for further analysis of the role of management in relation to soil quality.

Accordingly, not only were the three farm types identified in this study significantly different based on indicators for soil organic matter levels, but the farm types also aligned with general trends in management among sites, which indicated a link between soil organic matter levels and management. In particular, as the four indicators for soil organic matter collectively serve as a proxy for soil quality, our results suggest that soil quality indicators may show responsiveness to the impacts of short-term (3-5 years) management. In our study, crop diversity, crop rotational complexity, and tillage emerged as the strongest drivers of farm type differences, as shown by LDA coefficients (Table 7).

These results also coincided with average values for management variables compared across all three farm types (Table 6), though variables for ICLS and cover crop application overlapped considerably across all three farms. These cursory findings extend results from ongoing work from others (O'Neill et al. 2021; Williams et al. 2020; Culman et al. 2012; Wander et al. 1994), including a recent 4-year study by Sprunger et al. (2021)—which focused on organic corn systems in the Midwest. Sprunger et al. (2021) likewise reported strong links between soil metrics such as total N, total C, soil protein, and POXC—and on-farm management practices, such as crop rotation patterns, manure and cover crop application, and tillage. While extensive work has been done on organic corn and grain systems in the midwestern region of the US, our study provides new insight on the applicability of these common soil metrics in entirely different organic farming systems and climate regions—specifically on high-value vegetable farms operating in the dry, hot Mediterranean climates of northern California.

Our results also underscore the usefulness of on-farm interviews in developing management variables that are potentially linked to soil indicators (Prokopy et al. 2011). Whereas most previous studies have frequently utilized mail-in surveys that rely on binary (yes/no) responses from farmers to understand management (Mann et al. 2019; Sprunger et al. 2021), our study, following Guthman (2000) and others, highlights the uneven gradient in management practices that exists among organic farms and the importance of in-depth interviews (Carlisle et al. 2022). For example, rather than simply noting the presence or absence of tillage at a field site, our study accounted for the number of tillage passes per season that a farmer implemented on a particular field site, which required soliciting a range of responses from each farmer to create a congruent metric across all field sites. As displayed in Table 6, the mean values for frequency of tillage and crop abundance differed across the three farm types in our study; these management variables strongly separated Farm Type I from the other two farm types and weakly correlated with soil quality. On the other hand, crop rotational complexity generally separated all three farm types, but did not correlate with increasing soil quality. These results suggest that while certain management practices (eg, tillage) may increase soil organic matter pools as frequency decreases, some management practices (eg, crop rotational complexity) may require finding a "sweet spot" to achieve higher soil organic matter levels.

Relatedly, the implementation of ICLS did not appear to be as strong of a source of differentiation among the three farm types. One reason for this weak link between soil organic matter levels and ICLS may be due to the lack of a temporal component in the development of this soil metric. For example, some farms may have recently rotated livestock on their fields, while other farms may not have rotated livestock for several years on that particular field; our metric does not capture such spatial and temporal differences. Though limited studies on organic systems in California currently exist, previous studies in the midwestern US have found that the integration of livestock does increase organic matter levels on-farm (Maughan et al. 2009, Marriott and Wander 2006); however, based on our results, crop diversity, crop rotational complexity, and frequency of tillage present stronger influences than cover crop application and ICLS in differentiating working organic farms—at least in this particular context.

The significant role of soil texture

While management is undoubtedly an important driver of soil organic matter levels, our findings also suggest that soil texture may play a more significant role than management in determining levels of SOM than originally considered. Though management explained 18% of the variance among the three farm types, further analysis showed that soil textural class was the more dominant factor (28% explained variance) as shown in Figure 5; in fact, soil texture class was 44% greater (ie, nearly double) than management in explaining the three farm types. This important result from our study complements parallel findings from Sprunger et al. (2021), who also determined that soil textural class, rather than management, explained the largest amount of variation among the soil indicators they measured on their midwestern US-based organic corn systems (5-39% explained variance for management; 60-95% explained variance for textural class). Our combined findings provide an initial indication that regardless of the organic system—ie, crop, climate, and/or geography—soil texture is the more dominant determinant of soil indicators for soil quality rather than the diverse management practices applied to these systems (Hurisso et al. 2016).

This broader finding is significant because it supports emergent research that suggests that while management certainly contributes to soil quality, inherent characteristics of the soil (ie, texture) in a given field may place limits on achievable organic matter levels on organic farms (Devine et al. 2022). Based on our findings, it is evident that even along minimal gradients in soil texture class, organic matter levels strongly differ. It is not surprising that soil texture is an important determinant of SOM in these organic systems. Soil texture is known to be a strong control on soil organic matter dynamics across diverse ecological systems—not just agricultural systems—in part because organic (including N-containing) compounds, particularly those derived from soil microbes, are among those capable of stabilization by physical and chemical mechanisms, including aggregation, sorption on mineral surfaces, and entrapment within fine pores (Simpson et al. 2007; Lehmann and Kleber 2015; Six et al. 2002).

At a fundamental level, soils with greater amounts of clay tend to stabilize SOM on surfaces more than soils with high sand and/or silt content (Singh et al. 2018; Jilling et al. 2018; Needelman et al. 1999), as clay particles provide greater surface area through organo-mineral associations than other particle sizes (Kleber et al. 2021). For example, it has been shown in numerous previous studies that as clay content increases, the relative abundance of total soil N also increases (Grandy et al. 2009). Further other studies have shown that soil texture and structure can influence SOM chemistry, and therefore, SOM stabilization (Kögel-Knabner et al. 2008). Our study takes previous research in agricultural contexts one step further to show that while management is important to consider, soil texture may be the more dominant factor; however, based on our results, it is still unclear which direction soil texture may be driving SOM.

Nonetheless, our results highlight that contextualizing management in the native soil texture is essential to understand the limits of management imposed by pre-existing constraints of the soil. In practice, current emphasis in on-farm soil health research and quality assessments tends to focus on the importance of changing management to build healthy soils and improve soil quality without explicit consideration for soil texture (Williams et al. 2020; Lehmann et al. 2020). In this study, the gradient of soil textures across the farm fields sites was relatively limited (all sites ranged from clay loam to silty clay loam to loam) and *even so*—soil texture still explained a significant component of the variance observed compared to management. Given this outcome, our findings here reinforce the importance of using soil texture as a starting point for evaluating soil quality. Knowing the soil textural class of different fields may help farmers determine the management practices that have greatest potential for improving soil quality on farms with even small variances in soil textures; soil texture class may also help farmers better contextualize results of their soil health tests. Our study suggests that moving forward, soil texture should be more explicitly considered when making management recommendations to improve soil quality on organic farms.

That said, understanding the interactive effects between management and soil texture continues to be a gap in on-farm research and soil health assessment. Future studies might build on our approach and examine whether applying a similar suite of indicators to capture soil organic matter levels may yield similar connections with management in other organic farming contexts in California—and elsewhere in the US. Our study provides a potentially widely applicable method for developing a functional understanding of soil organic matter in complex agricultural landscapes. In this sense, the overall significance of the results of the cluster analysis highlights the efficacy of developing typologies to provide a useful tool for understanding the complexity of working agricultural landscapes. Importantly, the development of farm typologies allowed for additional analysis of other soil indicators for N cycling an availability—by using the farm types as a central tool for further investigation.

N cycling rates not strongly linked to soil organic matter

Though the range of gross N cycling rates from this study are comparable to N cycling values reported from previous studies in organic agricultural systems (Burger and Jackson 2003; Cookson et al. 2007; Bowles et al. 2015a), we found that farm types did not have significantly different gross (and net) N mineralization and nitrification rates—contrary to our initial hypothesis and despite that farm types strongly differentiated based on soil organic matter levels. These hypotheses were in part based on prior work with organic farms in this region that reported instances where inorganic N pools were low—well below established soil nitrate threshold sufficiency values—but that the crops themselves showed high production of, and sufficient N (Bowles et al. 2015a; Bowles et al. 2015b). Fields in which this trend was observed had the highest levels of soil C, and so in this previous study, it was hypothesized that higher rates of N production explained this observed trend.

However, nitrogen bioavailability for crops is not just a function of the gross production of inorganic N by microbes but is also influenced by physical soil characteristics within the rhizosphere, such as the local soil structure and mineralogy, plant root structure and associated mycorrhizal pathways, as well as accessibility of water to plants and soil microbes (Hartmann and Six 2022). These variable conditions in the rhizosphere are not captured by measuring N cycling rates but still directly influence bioavailability of N. For these reasons, the N cycling results of this study may not follow prior findings from Bowles et al. (2015b).

Still, we did observe an influence of soil organic matter levels on N cycling, particularly in terms of gross nitrification rates. As shown in the Linear Mixed Model results in Table 12, SOM indicators do appear to have an influence in predicting gross nitrification rates ($p=0.01$), even as the proportion of variation explained is modest ($R^2 = 0.095$). This slight trend is also evident in the boxplots (Figure 3f). The weak but significant link between soil organic matter levels and gross nitrification rates is important to highlight because these results suggest that building soil organic matter presents one way to increase nitrification rates and potentially crop N availability. Because the plant-soil-microbe N cycling system is strongly influenced by soil water content and soil structure, it is possible that gross N cycling indicators lack the responsiveness that SOM indicators exhbiti especially in scenarios where improved soil quality allows for crops to continue accessing soil microsites with available N (even as mass N flow decreases). Similarly, crops with more abundant and active mycorrhizal community associations can extend into smaller N-containing aggregates that may be otherwise locked up for crops with less root proliferation and hyphal associations. Additionally, it is also possible that changing microbial community composition in the soil may lead to greater immobilization of N, locking up available N but not necessarily impacting gross production of N. These plant-soil-microbe interactions that control availability of N (ie, differences in soil structure and crop root structure as well as differences in the microbial communities present) may not be detectable solely by measuring gross N flows.

While not significant, SOM indicators were also selected in the development of the LMM (Table 11) for gross mineralization rates as well. These results are congruent with previous research looking across ecosystem types that reported a relationship between N cycling rates and SOM indicators. For example, a meta-analysis published by Booth et al. (2005) that examined woody, grass, and agricultural ecosystems found a strong positive relationship between indicators for SOM (eg, total N, total C) and gross N mineralization. It is likely that in this prior study, the range of ecosystem types analyzed were sufficiently broad to detect a significant trend between indicators for SOM and N cycling. However, in our context, which encompasses agricultural systems only—it is possible that previously established trends are less detectable within this narrower range of ecosystem type. As shown in Figure 1 (in Booth et al. 2005), if the range of ecosystem type is constrained to include only agricultural systems, the relationship between indicators for SOM and gross N mineralization is less evident.

In summary, our results suggest that SOM indicators, while not significant, do play a role in influencing N cycling across the farm systems studied here. While initially, we found it surprising that N cycling soil indicators were not strongly linked to SOM indicators, one known limitation of measuring gross N mineralization and nitrification in the field is that while gross N production of inorganic N relay supply of available N to crops, gross rates in our case represent *potential* rates standardized to temperature and moisture—and therefore do not represent *in situ* rates found directly in the field. Moreover, using gross N production of inorganic N as an indicator for soil N cycling also poses inherent limitations for determining actual available N beyond those created by field conditions, as discussed above. However, while measuring gross N production of inorganic N may provide a more limited applicability for quantifying N cycling than originally hypothesized, the lack of a strong relationship between common soil indicators for organic matter levels and gross rates of soil N cycling does not necessarily mean that building organic matter with intentional management does not lead to greater N availability for crops.

For example, a recent study by Wade et al. (2020) that used identical indicators to measure soil organic matter levels in the midwestern (Corn Belt) region of the US found that these indicators for soil quality do indeed influence supply of N—based on crop responses (ie, yield). While this recent study focused on yield response to fertilizers and their relationship to soil health and soil quality and considered biogeochemical processes as intact (rather than mechanistically as we do here), we speculate that the influence of soil quality on N supply determined by Wade et al. (2020) is not as detectable when measuring gross N cycling directly. We suggest that there may be circumstances where N cycling indicators are not as responsive to N supply, but soil quality is still improving. Such circumstances can arise for example when minerals in the soil lock up available N or when soil microsites create differences in N cycling that is not reflective of actual

N supply to crops. In this sense, soil organic matter indicators (ie, total C, total N, POXC, and soil protein) better reflect local soil conditions, such as soil structure and root structure of crops, that overcome limitations imposed by mineralogy and/or soil microsites. For this reason, these soil organic matter indicators are both more comprehensive and more responsive for measuring N availability than N cycling indicators. As Grandy et al. (2022) point out, after a century of research, few indicators provide better insight to N availability than total soil N content (Ros et al. 2011).

Grandy et al. (2022) also highlighted that indicators for soil organic matter, such as those used in our study, represent soil metrics with a slow turnover rate as compared to the fast turnover rate among indicators for N cycling (Daly et al. 2021). This difference in soil indicator turnover rate may also be useful to consider in our study, as it is possible that gross N flows may have a faster turnover rate than SOM indicators and are therefore less responsive when compared to soil quality indicators and existing management regimes. Because our study focused on within season dynamics, the incongruity between soil indicator turnover rates is likely intensified. In addition, because our on-farm study examined cumulative impacts of diverse management approaches on N availability, it is also possible that these differences in soil indicator responsiveness lacked sensitivity not only due to differences in indicator turnover rates but also because the indicators for available N measured here may be more sensitive to management practices not explicitly captured in this study (eg, compost application, application of leguminous versus non-leguminous cover crops, etc). Likewise, given the strong influence of soil texture we found, soil clay content and mineralogy may play a more dominant role in influencing N cycling, potentially obscuring links to management in this context (Gardner and Drinkwater 2009). In particular, clay content strongly influences stabilization of organic N (and ammonium) through the formation of aggregate protected organic matter and through the preservation of microbial biomass, which ultimately limits bioavailable N (Ros et al. 2011).

CONCLUSION

Results of our on-farm study highlight the usefulness of applying indicators for soil organic matter not only to differentiate among organic farms in this context, but also to create a gradient in soil quality used for further analysis. We show that these indicators for soil quality are particularly informative when used to create farm typologies which can be then applied in further analysis of relationships, such as to management, soil edaphic characteristics, and/or other soil indicators. Though N cycling indicators proved to be less compelling in differentiating among organic farms along the soil quality gradient, this outcome may be due to limitations posed by gross N flows in detecting differences in soil microsites, root proliferation, and microbial immobilization within the broader plant-soil-microbe system. In this study, we did not incorporate information about crop nitrogen uptake, yields, or if crops exhibited nitrogen limitations, which could be useful to explore in future studies. Nevertheless, the suite of indicators applied in this study—total N, total C, soil protein, and POXC—together provide a valuable starting point for understanding N availability and soil quality on working organic farms.

While the gradient in soil quality that we detected across farm types was strongly driven by management, we found that soil texture played a more dominant role than management in explaining this gradient. Our results emphasize the importance of contextualizing management in native soil texture in order to understand the limits of management imposed by pre-existing constraints of the soil. Additional research on the key role of soil texture, particularly on organic farms with even small variation in soil textures, may help farmers to determine the management practices that have greatest potential for improving soil quality. To this end, our work emphasizes the strong interplay between both management and soil texture in influencing soil quality. Future work might incorporate more information about the timing of application for management practices, in order to more closely synchronize this data with soil indicators. The role of soil texture is clearly more important than originally thought, and should be more explicitly incorporated in soil health and quality assessments moving forward.

TABLES

Table 1. Crop types planted during late spring-summer of 2019 and soil properties associated with 27 farm field sites in Yolo County, California, USA. Soil edaphic characteristics for all sites sampled at a depth 20cm.

Site	Crop type(s)	Soil Texture Class	Sand (%)	Clay (%)	pH
1	Tomato	Loam	49%	18%	7.3
2	Pepper, squash, beans	Loam	38%	19%	7.6
3	Seedless watermelon	Loam	37%	20%	7.2
4	Tomato, onion, turnip, kale	Silty clay loam	18%	34%	7.3
5	Onion	Loam	38%	23%	7.4
6	Tomato	Clay loam	23%	29%	7
7	Summer squash, pumpkin, melon, cucumber, basil	Clay loam	32%	27%	7.5
8	Tomato, pepper, summer squash, tomatillo, eggplant, onion	Loam	29%	26%	7.5
9	Summer squash, cucumber, basil	Loam	38%	23%	7.4
10	Tomato	Loam	51%	18%	7.3
11	Tomato	Clay loam	24%	27%	7.3
12	Beet	Silty clay loam	20%	34%	6.7
13	Tomato, pepper, cucumber, summer squash	Loam	42%	18%	7.1
14	Summer squash	Loam	50%	19%	7.1
15	Onion	Loam	27%	24%	7.6

16	Summer squash	Silty clay loam	22%	34%	7.5
17	Strawberry	Silty clay loam	15%	38%	7.4
18	Leek, celery root, pepper	Clay loam	32%	29%	7.4
19	Safflower	Silty clay loam	18%	33%	7.1
20	Tomato, basil, sunflower	Clay loam	27%	28%	7.6
21	Tomato, melon	Loam	32%	25%	7.6
22	Summer squash, beans, corn	Loam	31%	25%	7.6
23	Summer squash, melon, cucumber	Loam	48%	18%	7.2
24	Tomato	Clay loam	27%	29%	7.5
25	Safflower	Clay loam	23%	37%	7.1
26	Sunflower, safflower	Loam	43%	21%	7
27	Tomato	Clay loam	26%	30%	7.2

Table 2. Soil ammonium and nitrate concentrations, and both net and gross N mineralization and nitrification rates for all sites, including standard error (se) for each result. Measurements for all sites sampled at a depth of 20cm.

Site	Ammonium		Nitrate		Net Mineralization		Net Nitrification		Gross Mineraliz.		Gross Nitrific.	
	µg-N g-soil^{-1}	se	µg-N g-soil^{-1}	se	µg-N g-soil^{-1} day^{-1}	se	µg-N g-soil^{-1} day^{-1}	se	µg-N g-soil^{-1} day^{-1}	se	µg-N g-soil^{-1} day^{-1}	se
1	0.93	0.01	3.49	0.22	0.74	0.03	2.34	0.41	0.14	0.09	1.08	0.13
2	0.91	0.04	2.56	0.59	0.15	0.01	1.98	0.26	0.34	0.01	1.28	0.25
3	0.31	0.04	10.43	0.71	0.10	0.02	1.69	0.01	0.05	0.02	0.55	0.04
4	2.38	0.23	11.96	0.76	1.27	0.03	8.53	1.25	1.69	0.06	0.75	0.05
5	0.10	0.04	10.85	0.24	0.42	0.02	5.92	0.95	0.03	0.01	1.92	0.21
6	0.21	0.03	5.27	0.16	0.22	0.06	3.16	0.51	0.12	0.03	2.42	0.17
7	1.05	0.01	10.07	0.05	0.38	0.03	3.53	0.34	0.11	0.04	0.97	0.04
8	1.05	0.01	8.36	0.65	0.07	0.01	2.60	0.15	0.08	0.00	1.82	0.39
9	1.08	0.05	9.73	0.63	0.05	0.01	3.29	0.46	0.09	0.03	5.90	0.57
10	0.99	0.06	4.73	0.22	0.11	0.02	1.31	0.31	0.20	0.08	3.10	0.11
11	0.25	0.08	2.95	0.20	0.29	0.09	2.60	0.35	0.25	0.07	0.75	0.12
12	2.79	0.05	20.11	1.93	1.51	0.13	14.10	1.20	4.20	0.54	2.50	0.25
13	1.28	0.08	21.29	1.46	0.19	0.01	15.44	0.61	0.17	0.03	3.69	0.18
14	1.16	0.09	8.97	0.32	1.46	0.12	6.13	0.43	0.59	0.02	1.28	0.10
15	1.95	0.05	4.81	0.53	0.49	0.06	3.46	0.17	4.04	0.05	0.88	0.14
16	1.43	0.04	8.29	0.14	0.69	0.08	7.37	0.02	4.70	0.18	2.18	0.19
17	2.40	0.17	27.08	1.64	1.33	0.08	19.45	0.66	4.82	0.44	1.86	0.24
18	1.15	0.03	22.82	1.39	0.52	0.02	7.97	0.01	0.10	0.04	2.19	0.48
19	0.30	0.07	6.72	1.05	0.51	0.01	3.55	0.14	0.12	0.06	1.07	0.06
20	1.20	0.14	8.32	0.26	0.59	0.08	1.52	0.56	0.15	0.10	2.67	0.03
21	0.16	0.01	11.27	0.45	0.03	0.01	7.56	0.32	0.03	0.01	2.19	0.09
22	2.64	0.20	18.92	0.54	1.15	0.01	15.98	0.46	3.94	0.05	1.90	0.75
23	1.23	0.13	14.79	1.25	0.63	0.15	18.21	2.57	0.29	0.11	2.38	0.39
24	0.22	0.05	5.37	0.15	0.07	0.01	2.71	0.09	0.25	0.03	1.25	0.21

25	1.39	0.09	11.89	1.17	0.60	0.04	12.32	0.86	0.42	0.04	0.95	0.11
26	1.16	0.07	9.17	0.25	0.16	0.07	6.21	0.69	0.16	0.06	2.07	0.37
27	2.51	0.15	11.99	0.89	1.20	0.06	15.61	0.07	2.63	0.56	4.12	0.56

Table 3. Total soil nitrogen, total organic carbon, POXC (active carbon), and soil protein (available N) for all sites, including standard error (se) for each soil indicator. Measurements for all sites were sampled at a depth of 20cm.

Site	Total N		Total C		POXC		Soil Protein	
	mg-N kg-soil^{-1}	se	mg-C kg-soil^{-1}	se	mg-C kg-soil^{-1}	se	g-g soil^{-1}	se
1	0.11	0.023	1.36	0.079	456	34	5.1	0.4
2	0.11	0.010	0.97	0.035	374	14	2.4	0.1
3	0.07	0.014	0.77	0.033	308	28	2.7	0.1
4	0.10	0.002	1.47	0.037	429	25	2.6	0.0
5	0.12	0.011	1.84	0.117	530	43	6.4	0.5
6	0.10	0.014	1.23	0.035	280	19	2.6	0.1
7	0.17	0.009	2.40	0.240	707	41	7.5	0.4
8	0.12	0.008	1.20	0.073	225	35	2.4	0.2
9	0.13	0.016	1.79	0.083	588	21	5.2	0.2
10	0.11	0.018	1.80	0.285	673	29	6.9	0.8
11	0.11	0.004	1.06	0.046	337	39	2.2	0.1
12	0.14	0.008	1.37	0.034	309	15	3.7	0.1
13	0.21	0.006	2.21	0.082	784	21	8.7	1.3
14	0.15	0.012	1.44	0.074	536	27	5.1	0.3
15	0.12	0.008	1.02	0.128	276	22	1.9	0.2
16	0.14	0.011	0.94	0.044	356	41	2.1	0.1
17	0.21	0.015	2.18	0.187	774	33	5.8	0.3
18	0.21	0.028	2.22	0.085	678	38	5.8	0.4
19	0.15	0.010	1.34	0.024	415	26	2.5	0.1
20	0.23	0.012	2.43	0.181	826	34	7.0	1.0
21	0.11	0.011	0.87	0.089	327	39	1.9	0.2
22	0.12	0.016	1.13	0.019	387	21	2.8	0.1
23	0.21	0.003	2.26	0.176	899	83	8.9	0.6
24	0.11	0.015	1.03	0.004	302	11	1.9	0.0
25	0.13	0.010	1.09	0.046	323	37	2.6	0.2
26	0.17	0.010	1.65	0.254	657	32	5.3	0.2
27	0.16	0.016	1.44	0.115	468	4	3.0	0.1

Table 4. A summary of key soil management practices for all sites, including crop rotational complexity as an index; frequency of tillage based on the number of passes per season; crop abundance based on the total number of crop species at the whole farm level per acres farmed; the use of integrated crop livestock systems (ICLS) as an index; cover crop frequency based on the average number of cover crop (CC) plantings per year (measured over a 2-year period). See Methods for additional details.

Site	Crop Rotation	Tillage	Crops per Area	ICLS	Cover Crops
	Rotational Complexity Index	No. passes per season	Total no. crop species per acre farmed	Index	Average no. CC plantings per year
1	3.00	7	0.43	0.0	0.5
2	3.16	8	0.06	0.0	1
3	5.19	8	0.01	0.0	1
4	4.47	4	0.71	0.9	2
5	3.16	6	0.09	0.6	1
6	4.47	8	0.02	0.0	1
7	4.47	4	3.85	0.2	1
8	3.46	5	1.40	0.2	0.5
9	3.16	5	0.14	0.7	1
10	5.19	6	0.09	0.6	1
11	5.19	5	0.31	0.6	1
12	3.46	9	0.02	0.0	1
13	4.47	5	0.83	0.0	2
14	3.00	7	0.43	0.0	0.5
15	3.16	8	0.06	0.0	1
16	5.19	8	0.01	0.0	1
17	4.47	4	0.71	0.9	2
18	3.16	4	1.67	1.0	2
19	4.47	8	0.02	0.0	1
20	4.47	4	3.85	0.2	1
21	3.46	5	1.40	0.2	0.5
22	3.16	5	0.14	0.7	1
23	5.19	4	1.67	1.0	2
24	5.19	5	0.31	0.6	1
25	3.46	9	0.02	0.0	1
26	4.47	5	0.83	0.0	2
27	2.73	8	0.04	0.0	1

Table 5. Results from analysis of similarity (ANOSIM) of three farm clusters. Global results and paired test results detailed below. R values equal to 1 if all samples within a group are more similar to each other than any sample from different group(s), and is approximately zero if the similarity between and within groups are on average the same. A significance level is calculated by referring the observed value of R to its permutation distribution.

Global Test

Complete dataset: Global R∗ = 0.785 (p = 0.001)
Pairwise tests (R∗∗ values significant p = 0.001, R∗ values significant p = 0.01)

Compare	Farm Type I	Farm Type II	Farm Type III
Farm Type I	-		
Farm Type II	0.583*	-	
Farm Type III	0.982**	0.766**	-

∗Test statistic comparatively measuring the degree of separation of the groups

Table 6. Mean and standard error values for management practices by farm type (Farm Type I, N=6; Farm Type II, N=6; Farm Type III, N=15), including crop rotational complexity based on an index, frequency of tillage based on the number of passes per season, crop abundance based on the total number of crop species at the whole farm level per acreage farmed, the use of integrated crop livestock system (ICLS) based on an index, and cover crop (CC) frequency based on the average number of cover crop plantings per year (measured over a 2-year period). See Methods for additional details.

Farm Type	Crop Rotation	Tillage	Crop Abundance	ICLS	Cover Crops
	Rotational Complexity Index	No. passes per season	Total no. crop species per acre farmed	Index	Average no. CC plantings per year
I	4.7 ± 0.3	4.2 ± 0.4	2.0 ± 1.4	0.6 ± 0.4	1.7 ± 0.5
II	3.3 ± 0.5	6.0 ± 0.8	0.4 ± 0.2	0.3 ± 0.3	1.0 ± 0.5
III	4.0 ± 0.3	6.9 ± 1.2	0.3 ± 0.3	0.2 ± 0.3	1.0 ± 0.3

Table 7. Loading coefficients for Dimension 1 and Dimension 2, including variable breakdown for each loading based on Linear Discriminant Analysis (LDA). Two soil edaphic variables (% sand, % clay) and three key management variables (crop rotational complexity, frequency of tillage, and crop abundance) were applied in the analysis.

LDA Loadings		
Variable	**LD 1** (66.3%)	**LD 2** (33.6%)
% Sand	2.91	-2.28
% Clay	2.2	-2.53
Crop Rotation	-0.48	0.89
Tillage	0.27	0.05
Crop Abundance	0.47	1.29

Table 8. Classification error indicator statistics for Linear Discriminant Analysis (LDA), which shows the sensitivity, specificity, positive predicated values, and accuracy as a percent. Sensitivity is defined as the proportion of positive results out of the number of samples which were actually positive. Specificity refers to the proportion of negative results out of the number of samples which were actually negative. Positive predicted values is a measure of the correctly predicted positives that are actually positive. Accuracy is the number of correct classifications divided by the total number of samples in the set (ie, the sum of true positives and true negatives divided by the total samples, training and test sets).

LDA Indicator Statistics

Overall Accuracy: 90.9% ($p < 0.001$)

Indicators (%)	**Farm Type I**	**Farm Type II**	**Farm Type III**
Sensitivity	67	100	80
Specificity	100	75	100
(+) Predicted Val.	100	88	100
Accuracy	83	88	90

Table 9. Confusion matrix results based on training and test datasets (0.78 and 0.22, respectively) that show classification accuracy across the three farm types using Linear Discriminant Analysis (LDA). Of the test dataset (N=22) based on an initial training dataset (N=5), 20 test points were correctly classified as one of three farm types. Test points accurately predicted are highlighted in bold.

LDA Confusion Matrix			
	Actual		
Predicted	**Farm Type I**	**Farm Type II**	**Farm Type III**
Farm Type I	**2**	0	0
Farm Type II	1	**14**	1
Farm Type III	0	0	**4**

Table 10. Linear Mixed Model (LMM) results for predicting potential gross ammonification. Selected indicators and their respective coefficient and p-values are included. SOM Indicator represents Dimension 1 of the cluster analysis, that includes four key indicators for soil organic matter. Ammonium refers to soil ammonium concentrations.

Model 1

Overall R^2 – 0.55 | Intercept – 0

Variables	**Coefficient**	**p-value**	**Significance**
Ammonium	0.547	<0.0001	***
% Sand	-0.233	0.042	*
SOM Indicators	-0.189	0.1	-

(p-values *** significant p = 0; ** significant p = 0.001; * significant p = 0.01)

Table 11. Linear Mixed Model (LMM) results for predicting potential gross nitrification. Selected indicators and their respective coefficient and p-values are included. SOM Indicator represents Dimension 1 of the cluster analysis, that includes four key indicators for soil organic matter. Crop abundance is based on the total number of crops per acre farmed. See Methods for additional details.

Model 2

Overall R^2 – 0.095 | Intercept – 0

Variables	**Coefficient**	**p-value**	**Significance**
SOM Indicators	0.364	0.027	*
Crop Abundance	-0.186	0.25	-

(p-values *** significant p = 0; ** significant p = 0.001; * significant p = 0.01)

FIGURES

Figure 1. K-means cluster analysis results showing three clusters along Dimension 1 (x-axis), which explains 86.7% of the separation of field sites, and Dimension 2 (y-axis), which explains 9.5% of the separation. In total, both dimensions explain 96.2% of the separation of field sites. Clusters labelled based on emergent farm types (Farm Type I, II, III).

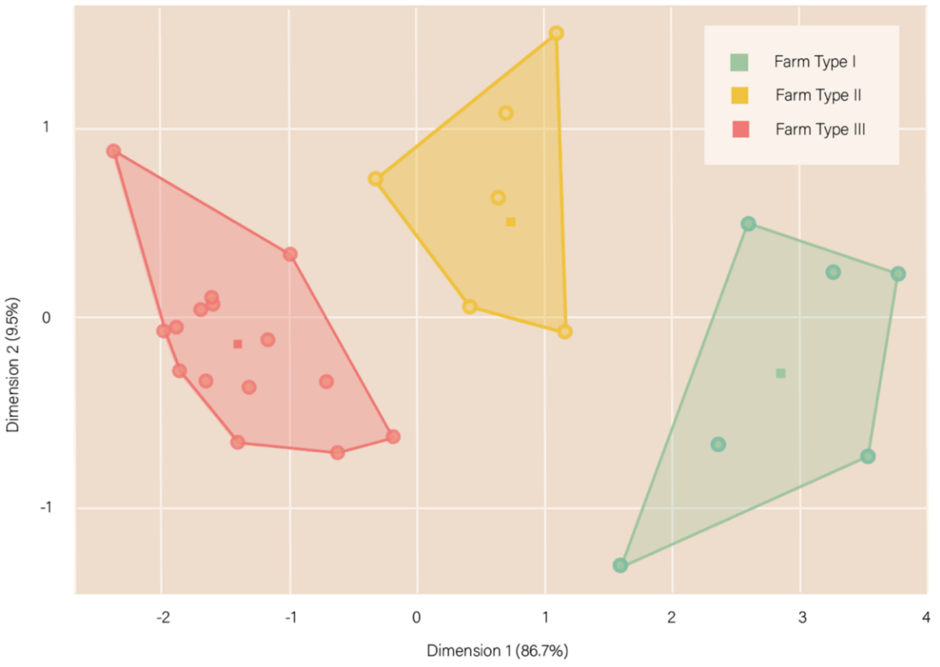
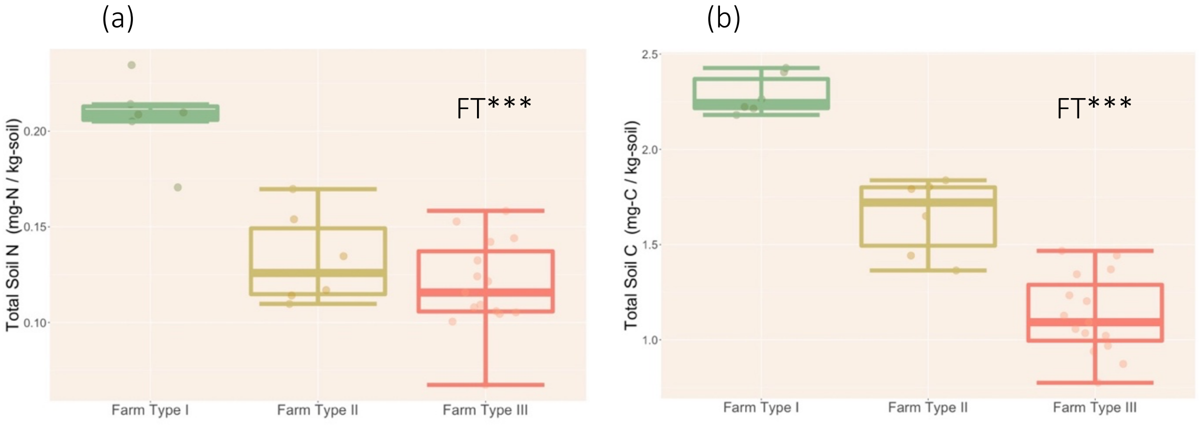


Figure 2. A comparison of farm types (Farm Type I, II, III) on x-axis across all four indicators for soil organic matter, including total soil nitrogen, total organic carbon, POXC, and soil protein. Shown are means ± 95% confidence intervals. Inset in each panel are results of one-way ANOVA (FT = ANOVA), where *p< 0.05; **p< 0.01; ***p< 0.001.



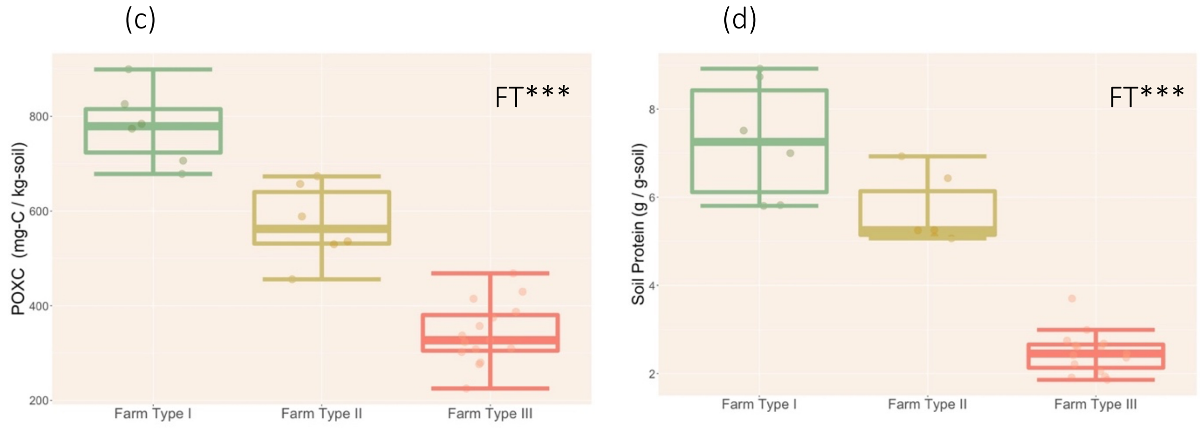
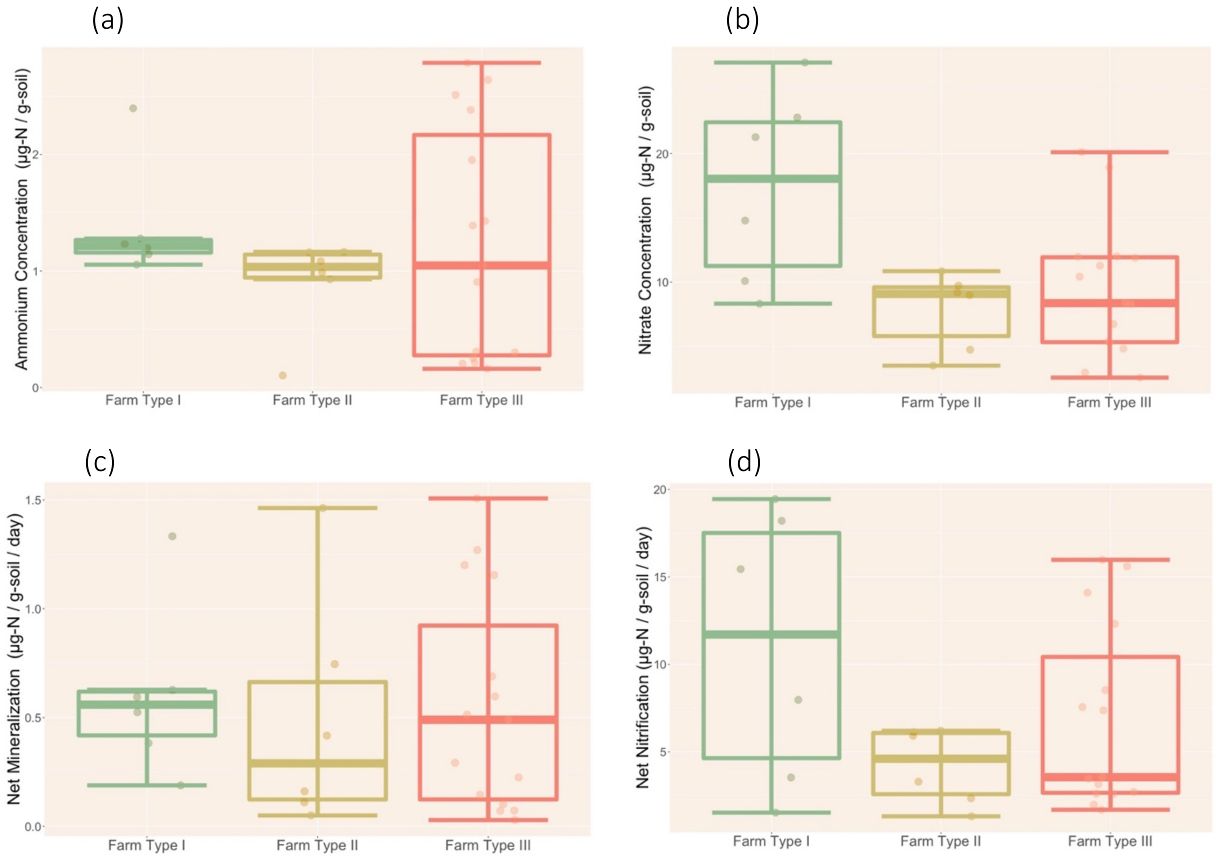


Figure 3. A comparison of farm types (Farm Type I, II, III) on x-axis across all six N cycling variables (y-axis), including soil ammonium and nitrate concentrations, and both net and gross N mineralization and nitrification rates. Shown are means ± 95% confidence intervals. Inset in each panel are results of one-way ANOVA (FT = ANOVA), where *p< 0.05; **p< 0.01; ***p< 0.001.



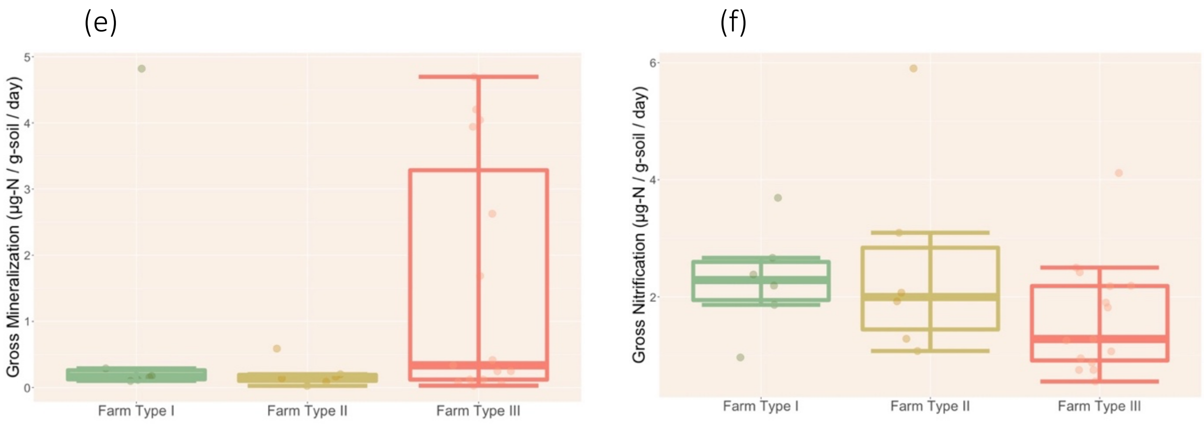


Figure 4. Visualization of LDA (Linear discriminant analysis) results showing the distribution of the test dataset along the first dimension (LD1; 66.3% of variance explained) and the second dimension (LD2; 33.6% of variance explained). Individual points show the test set (N=22) derived from the original field sites (N=27), while the ovals show the boundary range for each farm type based on the spatial distribution of the test dataset.

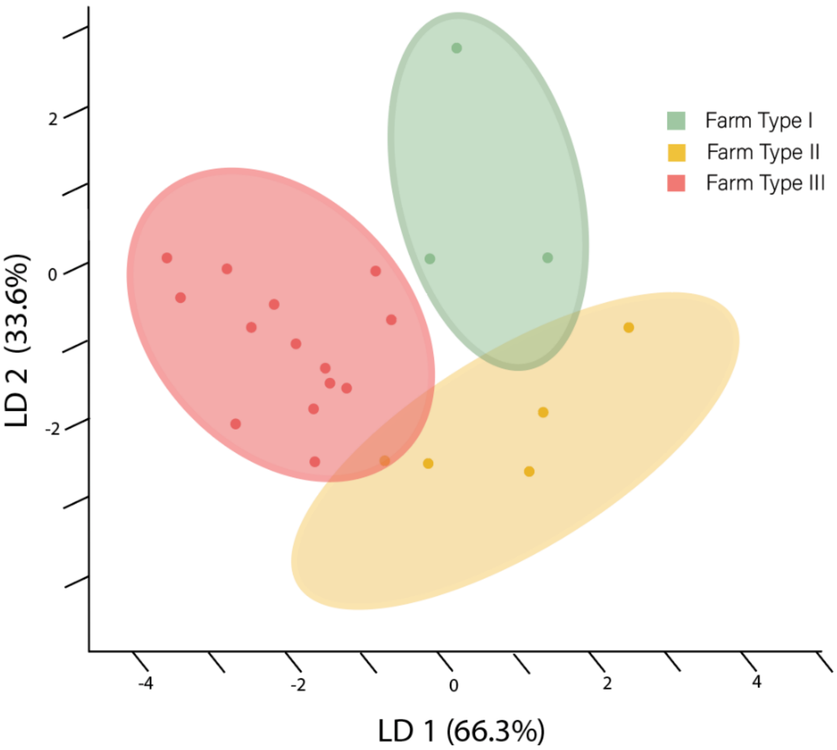
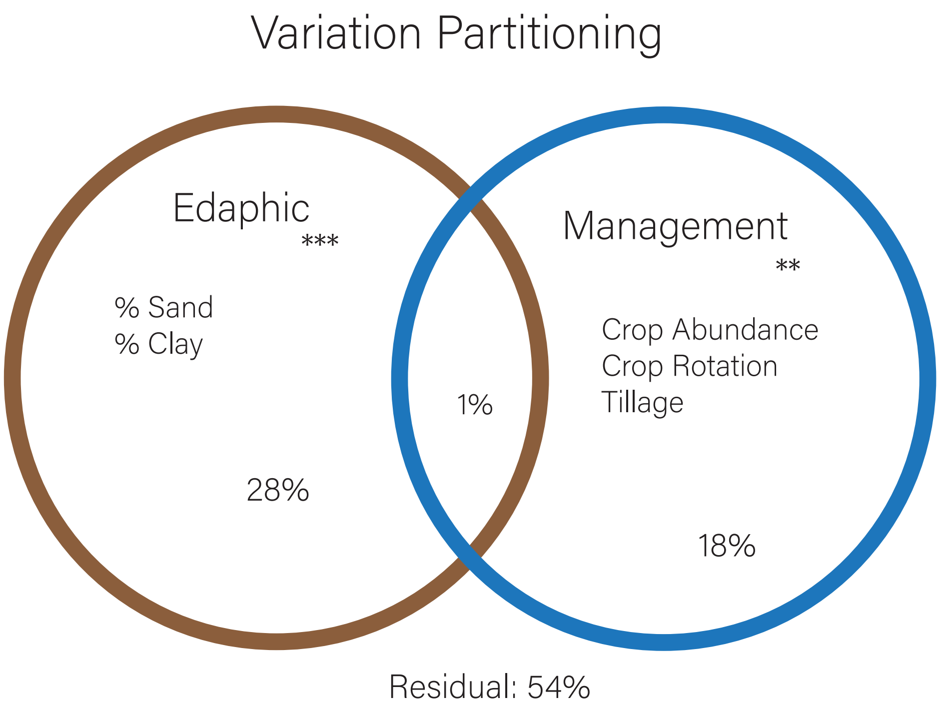


Figure 5. Variation partitioning of soil texture and management predictors. Soil texture predictors significant to p< 0.001 (***) and management predictors significant to p< 0.01 (**).



Chapter III

Soil health and fertility management in practice: A case study of farmer knowledge and soil indicators on working organic farms in a farming region of northern California

ABSTRACT

Though farmer perspectives on the adoption of soil health practices are well documented in the literature, inclusion of farmer knowledge as part of the knowledge-making process of emergent soil health research in the United States remains sparse. Yet, farmers possess extensive place-based knowledge of their soil and farming systems, and are uniquely positioned to contribute their local and ecological knowledge to the soil health research arena. Most notably, ongoing development of metrics to quantify on-farm soil fertility—a key expression of soil health—does not currently include farmer knowledge of soil fertility as part of the research process. Here, we address this gap in the literature, and provide a case study to model future inclusion of farmer knowledge in assessing on-farm soil fertility. We focus our study on a unique group of 13 organic farms in Yolo County, CA. Using a combination of qualitative, in-depth field interviews with farm owners and quantitative on-farm surveys that measured key indicators for soil fertility, we first queried farmers about the extent to which they think about key nutrients related to soil fertility; we also asked farmers about the usefulness of existing indicators for soil fertility in their informing their management. We then examined if soil indicators were able to detect differences between fields deemed by farmers as "most challenging" or "least challenging" in terms of maintaining soil fertility. Our study found that while farmers are aware of key nutrients related to soil fertility, to ensure crop nutrient availability in their soil they placed greater emphasis on creating soil environmental conditions through a synergy of multiple management practices. For this reason, most farmers in this study did not find soil tests to be useful or applicable to their farm operation. We also found that most key indicators for soil fertility, with the exception of total soil nitrogen, were not able to detect differences between fields designated by farmers on the high and low end of soil fertility on their farms. Our findings underscore the overemphasis of crop nutrient availability in building on-farm soil fertility, and the importance of calibrating indicators for soil fertility within the local soil context by working in collaboration with local farmers. Specifically, inclusion of farmer knowledge of soil structure and texture, field variability, and management history represents an important starting point for assessing soil health and fertility on working organic farms.

INTRODUCTION

In recent years, the concept of "soil health" in the United States (US) has become codified as a research and policy tool to unify efforts towards 1) improving soil function on farms, and more broadly 2) building on-farm resilience (Lehman et al. 2015; Wander et al. 2019; Peterson et al. 2018). While the exact definition of "soil health" continues to evolve, the concept generally refers to "the continued capacity of soil to function" in a way that sustains ecological, environmental, and human needs (USDA-NRCS, 2012; Lehmann et al. 2020). On the technical front, soil health research has focused on effective and efficient ways to measure and improve soil health, and on quantifying benefits associated with building soil health (Stewart et al. 2018; Wade et al. 2022; Wood and Blankinship 2022).

Concurrent research has also placed particular emphasis on the role of "innovative" on-farm management practices in building soil health and promoting on-farm resilience (Bagnall et al. 2020). This research has taken a practice-centric approach that primarily uses social science methods to examine farmers' views or farmers' uses of specific practices, and has—importantly—generated insight into the adoption of key management practices related to soil health (Prokopy et al. 2019). Despite this work, to date, very few studies in the US explicitly incorporate farmer knowledge of soil health and soil management beyond farmer perspectives on the topic and/or farmer motivations for adopting soil health practices (Wade et al. 2021; Wirth-Murray and Basche 2020; Huynh et al. 2020; Gruver and Weil 2007). However, farmers possess wide and deep place-based knowledge of their soils that has the potential to advance work on soil health beyond its currently limited scope (see Chapter 1; Sūmane, et al. 2018).

Inclusion of farmer knowledge is integral if one outcome of ongoing research on soil health is to address both social *and* ecological resilience. Farmers are uniquely positioned to share their on-the-ground *social* realities and their local *ecological* knowledge of their soils and farming systems (Sūmane et al. 2016; Gruver and Weil 2007). To be clear, inclusion of farmers in this research arena is essential if only to contribute farmer knowledge and farmer voices to the existing body of work—which to date has been lacking (Kloppenburg et al. 1991; Flora et al. 1992). This call for inclusion of farmer knowledge represents: 1) a departure from the majority of prior research in the US that tends to emphasize the advancement of research and policy agendas aimed at behavioral change (ie, increasing farmer adoption of soil health promoting management practices); and 2) simultaneously, a shift towards explicit inclusion of farmer knowledge (and ideally, farmers themselves) in the knowledge-making of emergent soil health research.

While farmer knowledge is certainly important and underutilized, consideration for quantitative assessments of soil health remains a critical component of advancing soil health. Available indicators to quantify soil health already exist and are widely applied both on farms and in scientific studies. These soil indicators prioritize so-called "principles of soil health" to assess health through evaluating soil function, usually emphasizing metrics for organic matter (OM) quality, nitrogen (N) availability, soil biological activity, and water cycling (Morgan & Cappellazzi 2021; USDA-NRCS, 2012). Currently, our understanding of how local farmer knowledge of soil health and management might interact with available soil health metrics is limited. Farmer inclusive research evaluating soil metrics is generally sparse—with only a handful of studies on mostly non-organic farms in the midwestern US (Gruver and Weil 2007; Liebig and Doran 1999; Garlynd et al. 1994). Yet, if a central goal of soil health research is to further develop the concept of soil health, and also to better understand the key management practices associated with this concept, then examining the ways in which local farmer knowledge can interact with quantitative soil metrics evaluated in the field may offer a complementary approach to prior work (O'Neill et al. 2021; Sprunger et al. 2021; Gruver and Weil 2007).

In this study, we focus on a functional expression of on-farm soil health related to crop production—soil fertility. Soil fertility is generally defined as the capacity of a soil to supply the nutrients needed for crop growth, and is therefore linked to crop nutrient availability (Lehmann et al. 2020). More broadly, soil fertility underpins the productivity of agricultural systems, and has social and environmental implications related to fertilizer application and nutrient management (Grandy et al. 2022; Bowles et al. 2018; Lehmann et al. 2020). Ongoing efforts to measure soil fertility have placed particular emphasis on how farmers consider key nutrients, such as nitrogen, as part of their farm management (O'Connell and Osmond 2022). Although metrics for quantifying aspects of soil fertility have existed for several decades now, it is less understood how—if at all—these commonly available metrics for soil fertility actually inform farmers and their fertility programs (Sprunger et al. 2021; O'Neill et al. 2021). Moreover, there currently is a gap in the literature in mapping how these knowledge spheres—farmer knowledge of soil fertility and soil indicators for soil fertility—interact to co-produce new insights to evolve this component of soil health research. Toward this end, our central questions with this study were to examine—

1. To what extent, and in what way, do farmers think about key nutrients—in terms of soil fertility—on their farm?
2. How useful are existing soil tests to farmers in informing their soil fertility programs and/or management more generally on their farm?
3. Can commonly available soil metrics detect differences between fields deemed by farmers as "most challenging" or as "least challenging"—in terms of maintaining soil fertility?

To investigate these questions, we applied a case study approach, engaging in on-farm research of 13 organic farms and their respective farm owners in Yolo County, California, USA—a region where this type of farmer inclusive soil health research has been limited to date. We used qualitative, in-depth field interviews in combination with quantitative field sampling and subsequent laboratory analysis. This research focused on Yolo County in particular, because of its unique role as a hub for innovative, high-value organic vegetable production (see Chapter 1). These thirteen organic farmers specifically—because of their historical relationship to their land and their intimacy with the physical place they farm—collectively represented a salient case study through which to understand soil health and fertility from a grounded perspective. More broadly, we led this work with a Farmer First approach (see Methods) in order to give voice to organic farmers of this region, and to provide a model for future inclusivity of farmer knowledge in the growing body of work on soil health.

METHODS

Study site, farm selection, and participant recruitment

We conducted our experiment on 13 farms in Yolo County, California, on unceded Patwin-speaking Wintun Nation tribal lands—located along the western side of the Sacramento Valley between late March 2019 and December 2020. The region is characterized by Mediterranean-type climate with cool, wet winters and hot, dry summers. Precipitation in the 2019 water year 2019 was 807 mm—the fifth wettest winter (2018/2019) on record. The mean maximum and minimum temperatures were 33.9°C and 15.5°C, respectively for July 2019. Mean annual maximum and minimum temperatures for 2019 were 24°C and 9.8°C, respectively. All farm sites were on similar parent material (mixed alluvium derived from sandstone and shale). Most farms were situated on either loam, clay loam, or silty clay loam.

All 13 farms selected for this soil health study were located in Yolo County (or <2 miles from the border). The organic farms represent a majority (>80%) of the farms in the region with a diversified array of vegetable and fruit crops that sell to a variety of consumer markets, including farmers' markets, wholesale markets, and restaurants. The 13 farmers interviewed represent 13 individuals who oversee management and operations on their farms. These individuals were most often the primary owner and operator of the farm, and made key management decisions on their farm.

To identify potential participants for this study, we first consulted the USDA Organic Integrity database and assembled a comprehensive list of all organic farms in the county (N=114). Next, with input from the local University of California Cooperative Extension (UCCE) Small and Organic Farms Advisor for Yolo County, we narrowed the list of potential farms by applying several criteria for this study: 1) organic operation on the same ground for a minimum of 5 years; 2) a minimum of 10 years of experience in organic farming; and 3) a focus on growing diversified fruit and vegetable crops.

These requirements significantly reduced the pool of potential participants. In total, 16 farms were identified to fit the criteria of this study (IRB ID:2018-04-11014). These 16 farmers were contacted with a letter containing information about the study and its scope. To establish initial trust with farmers identified, we worked directly with the local UCCE advisor. Thirteen farmers responded and agreed to participate in the entirety of the study (including an initial field visit, summer field sampling, and an in-depth semi-structured interview).

Site selection and field sampling

Because this research is informed by a Farmer First approach—which emphasizes multiple ways of knowing and challenges the standard "information transfer" pipeline model that is often applied in research and extension contexts—farmers were viewed as experts and crucial partners in this research (Chambers et al. 1989; Chambers and Ghildyal 1985; Scoones and Thompson 1994; Drinkwater et al. 2016). As a result, farmers were considered integral to field site selection, and were not asked to change their management or planting plans. In addition to the Farmer First approach, we intentionally used a two-tiered interview process, in which we scheduled an initial field visit and then returned for an in-depth, semi-structured interview at a later date—after summer field sampling was complete. The overall purpose of the preliminary field visit was to help establish rapport and increase the amount and depth of knowledge farmers shared during the semi-structured interviews. The initial field visit typically lasted one hour and was completed with all 13 participants. Farmers were asked to walk through their farm and talk generally about their fields, their fertility programs, and their management approaches. The field interview also provided an opportunity for open dialogue with farmers regarding specific management practices and local knowledge (Morris 2006). Because local knowledge is often tacit, the field component was beneficial to connect knowledge shared by each farmer to specific fields and specific practices.

During the initial field visit, field sites were selected in direct collaboration with farmers. First, each farmer was individually asked to describe their understanding of soil health and soil fertility. Based on their response, farmers were then asked to select two field sites within their farm: 1) a field that the farmer considered to be exemplary in terms of their efforts towards building soil fertility (Field A, at the high end of soil fertility on their farm); and 2) a field the farmer considered to be a challenge in terms of their efforts towards maintaining soil fertility (Field B, at the low end of soil fertility on their farm). Essentially, farmers were asked, "Can you think of a field that you would consider 'least challenging' in terms of building soil fertility on your farm?" (ie, Field A) and "Can you also think of a field that you would consider 'most challenging' in terms of building soil fertility on your farm?" (ie, Field B). Farmers would often select several fields, and through back-and-forth dialogue with the field researcher, together would arrive at a final field selected for each category (ie, Field A and Field B). Only fields with all summer vegetable row crops (eg, no fields with cover crops or fallow fields) were selected for sampling. For each site, farmers delineated specific management practices, including information about crop history and crop rotations, bed prepping if applicable, the number of tillage passes and depth of tillage, rate of additional N-based fertilizer inputs, and type of irrigation applied.

Following field site selection, soil sampling was designed to capture indicators of soil fertility in the bulk soil at a single timepoint. Fields were sampled mid-season at peak vegetative growth when crop nitrogen demand was the highest. This sampling approach was intended to provide a snapshot of on-farm soil health and fertility. Because the farms involved generally grow a wide range of vegetable crops, we designed the study to have greater inference space than a single crop, even at the expense of adding variability. As such, we collected bulk soil samples that we did not expect to be strongly influenced by the particular crop present.

Field sampling occurred over the course of four weeks in July 2019. To sample each site, a random 10m by 20m transect area was placed on the field across three rows of the same crop. Within the transect area, three composite samples each based on five sub-samples were collected approximately 30cm from a plant at a depth of 20cm using an auger (see Figure 1). Subsamples (500g fresh weight soil) were composited on site and mixed thoroughly by hand for 5 minutes before being placed on ice and immediately transported back to the laboratory.

Laboratory Processing

Soil samples were preserved on ice until processed within several hours of field extraction. Each sample was sieved to 4mm and then either air dried, extracted with 0.5M K_2SO_4, or utilized to measure net mineralization and nitrification (see below). A batch of air-dried samples were measured for gravimetric water content (GWC), which was determined by drying fresh soils samples at 105°C for 48 hours. Moist soils were immediately extracted and analyzed colorimetrically for NH_4^+ and NO_3^- concentrations (detection limit of approximately 10 ppm) using modified methods from Miranda et al. (2001) and Forster (1995). Additional volume (50mL) of extracted samples were subsequently frozen for future laboratory analyses.

To determine soil textural class, another batch of air-dried samples were further sieved to 2mm and subsequently prepared for analysis using the "micropipette" method (Miller & Miller 1987). Water holding capacity (WHC) was determined using the funnel method, adapted from Geisseler et al. (2009), where a jumbo cotton ball thoroughly wetted with deionized water was placed inside the base of a funnel with 100 g soil on top. Deionized water was added and allowed to imbibe into the soil until no water dripped from the funnel. The soil was allowed to drain overnight (covered with parafilm). A subsample of this soil was then weighed and dried for 48 hours at 105°C. The difference following draining and oven drying of a subsample was defined as 100% WHC.

Additional air-dried samples were sieved to 2mm, ground and then analyzed for total organic carbon (C), total soil nitrogen (N), soil protein, and pH at the Ohio State Soil Fertility Lab (Ohio, USA). The former two analyses were conducted using an elemental analyzer (varioMax cute Elemental Analyzer; detection limit of approximately 10 ppm). Soil protein was determined using the autoclaved citrate extractable soil protein method outlined by Hurisso et al. (2018).

Remaining air-dried samples were sieved to 2mm, ground, and then analyzed for POXC using the active carbon method described by Weil et al. (2003), but with modifications as described by Culman et al. (2012). In brief, 2.5g of air-dried soil was placed in a 50mL centrifuge tube with 20mL of 0.02 mol/L $KMnO_4$ solution, shaken on a reciprocal shaker for exactly 2 minutes, and then allowed to settle for 10 minutes. A 0.5mL aliquot of supernatant was added to a second centrifuge tube containing 49.5mL of water for a 1:100 dilution and analyzed at 550 nm. The amount of POXC (mg-C/kg air-dried soil) was determined by the loss of permanganate due to C oxidation (Hurisso et al. 2016).

Net mineralization and nitrification

To measure net N mineralization and nitrification in soil samples, fresh soil subsamples were incubated in 50mL falcon tubes using a parafilm cover applying methods adapted from Wade et al. (2016). Prior to incubation, each subsample was weighed to 7g and adjusted to 60% water holding capacity. Each sample had three parallel sets of subsamples for each incubation period (t = 1, 28, and 54 d).

At the end of each incubation period, soil samples were extracted with 0.5M K_2SO_4, placed on the shaker for 30 minutes, centrifuged for 3 minutes at 7500 rpm, and then filtered using Whatman #42 filter paper. Standard colorimetry (as described in section above) was used to measure NH_4^+ and NO_3^- concentrations for each sample at each time point. Net N mineralization and nitrification were calculated as the cumulative change in soil inorganic N (eg, NH_4^+ and NO_3^-) between a given sampling date (*t*) and the initial inorganic N levels (t = 1 d).

Semi-structured interviews

After the initial field visit and following summer field sampling, all 13 farmers were contacted to participate in a follow up visit to their farm, which consisted of a semi-structured interview followed by a brief survey. The semi-structured interview is the most standard technique for gathering local knowledge (Huntington 1998). These in-depth interviews allowed us to ask the same questions of each farmer so that comparisons between interviews could be made. In-person interviews were conducted in the winter, between December 2019 – February 2020; three interviews were conducted in December 2020. All interviews were recorded with permission from the farmer and lasted about 2 hours.

To develop interview questions for the semi-structured interviews (see Appendix, Supplement A), we established initial topics and thematic sections first. We consulted with two organic farmers (located in Marin County, CA) to develop final interview questions. The final format of the semi-structured interviews was designed to encourage deep knowledge sharing. For example, the interview questions were structured such that questions revisited topics to allow interviewees to expand on and deepen their answer with each subsequent version of the question. Certain questions attempted to understand farmer perspectives from multiple angles and avoided scientific jargon or frameworks whenever possible. Most questions promoted open ended responses to elicit the full range of possible responses from farmers. We used an open-ended, qualitative approach that relies on in-depth and in-person interviews to study farmer knowledge (Prokopy 2011).

In the semi-structured interview, farmers were asked a range of questions that included: their personal background with farming and the history of their farm operation, their general farm management approaches, as well as soil management approaches specific to soil health and soil fertility, such as key nutrients in their consideration of soil fertility, and their thoughts on soil tests (ie, the general usefulness and applicability of soil tests on farm). A brief in-person survey that asked several key demographic questions was administered at the end of the semi-structured interviews. Interviews were transcribed, reviewed for accuracy, and uploaded to NVivo 12, a software tool used to categorize and organize themes systematically based on research questions (Maher et al. 2018). Through structured analysis of the interview transcripts, key themes were identified and then a codebook was constructed to systematically categorize data related to soil health and soil fertility (Neuman and Kreuger 2003). We summarize these results in table form.

Statistical analyses

To unpack differences between Fields A (eg, "least challenging" field) and Fields B (eg, "most challenging" field) across all farms, we applied a multi-step approach. We first conducted a preliminary, global comparison between Fields A and Fields B across all farms using a one-way analysis of variance (ANOVA) to determine if Fields A were significantly different from Fields B for each indicator for soil fertility. Then, to develop a basis for further comparison of Fields A and Fields B, we considered potential links between management and soil fertility. To do so, we developed a gradient among the farms using a range of soil management practices detailed during the initial farm visit. These soil management practices were based on interview data from the initial farm visit, and were also emphasized by farmers as key practices linked to soil fertility. The practices used to inform the gradient included cover crop application, amount of tillage, crop rotation patterns, crop diversity, the use of integrated crop and livestock systems (ICLS), and the amount of N-based fertilizer application.

Cover crop frequency was determined using the average number of cover crop plantings per year, calculated as cover crop planting counts over the course of two growing years for each field site. Tillage encompassed the number of tillage passes a farmer performed per field site per season. To quantify crop rotation, a rotational complexity index (RCI) was calculated for each site using the formula outlined by Socolar et al. (2021). To calculate crop diversity, we focused on crop abundance, the total number of crops (at the species level) grown per year at the whole farm level was divided by the total acreage farmed. To determine ICLS, an index was created based on the number and type of animals utilized (eg, chickens, cows, pigs, sheep, etc). Lastly, we calculated the amount of additional N-based fertilizer applied to each field (in kg-N per acre).

In order to group, visualize, and further explore links with indicators for soil fertility, all soil management variables were standardized ($\mu = 0$ and $\sigma = 1$), and then used in a principal components analysis (PCA) using the factoextra package in R (Version 4.2.4). In short, these independent management variables were used to create a composite of several management variables. Principal components with eigenvalues greater than 1.0 were retained. To establish the gradient in management, we plotted all 13 farms using the first two principal components, and ordered the farms based on spatial relationships that arose from this visualization using the nearest neighbor analysis (RANN package in R, Version 2.6.1).

To further explore links between management and soil fertility, we used the results from the PCA to formalize a gradient in management across all farms, and then used this gradient as the basis for comparison between Field A and Field B across all indicators for soil fertility. Using the ggplot and tidyverse packages (R, Version 4.0.5), we displayed the difference in values between Field A and Field B for each indicator for soil fertility sampled at each farm using bar plots. We also included error bars to show the range of uncertainty in these indicators for soil fertility.

Lastly, we further compared Field A and Field B for each farm using radar plots. To generate the radar plots, we first scaled each soil indicator from 0 to 1. Using Jenks natural breaks optimization, we then grouped each farm based on low, medium, and high N-based fertilizer application, as this soil management metric was the strongest coefficient loading from the first principal component (PC 1). Using the fmsb package in R (Version 4.0.5), we used an averaging approach for each level of N-based fertilizer application to create three radar plots that each compared Field A and Field B across the eight indicators for soil fertility.

RESULTS

Farmer and farm operation background

Farmers provided an overview of their farm operation, including farm size (in acres), the total number of crops each farm planted *per* growing season at the whole farm level, the types of crops planted in their field during the initial field visit (in late Spring 2019; Field A and Field B), the type and amount (originally reported by farmers in lbs/acre) of nitrogen-based fertilizer they applied on farm, and key aspects of soil health in their own words (Table 1). Farm sizes ranged from 15 to 800 acres, with about one third of farms in the 15 – 50-acre range, another third in the 100 – 450-acre range, and roughly a final third in the 500 – 800 acre-range. Farmers grew primarily summer crops, including tomato, a variety of cucurbits, strawberry, herbs, nightshades, root vegetables, and sunflower/safflower for oil. Farmers reported applying a range of external N-based organic fertilizers, including fish emulsion, Wiserg (a digested food byproduct liquid), pelleted chicken manure, and seabird guano, at varying rates (Table 1). On the low end, farmers applied <1 kg-N/acre, and on the high end, farmers applied 90 – 180 kg-N/acre per season. About a third of farmers applied 2 – 25 kg-N/acre of N-based fertilizer.

Key aspects of soil health and fertility

Farmer responses for describing key aspects of soil health were relatively similar and overlapped considerably in content and language (see Table 1). Specifically, farmers usually emphasized the importance of maintaining soil life and/or soil biology, promoting diversity, limiting soil compaction and minimizing disturbance to soil, and maintaining good soil structure and moisture. Several farmers also touched on the importance of using crops as indicators for monitoring soil health and the importance of limiting pests and disease. Discussion of the importance of promoting soil life, soil biology, and microbial and fungal activity had the highest count among farmers with ten mentions across the 13 farmers interviewed. Next to this topic, minimizing tillage and soil disturbance was the second most discussed with six of 13 farmers highlighting this key aspect of soil health. The importance of crop health as an indicator for soil health also surfaced for five out of 13 farmers.

In addition to discussing soil health more broadly, farmers also provided in-depth responses to a series of questions related to soil fertility—such as key nutrients of interest on their farm, details about their fertility program, and the usefulness of soil tests in their farm operation—summarized in Table 2. When asked to elaborate on the extent to which they considered key nutrients, a handful of farmers readily listed several nutrients, including nitrogen, phosphorous, potassium (N, P, K), and other general macronutrients (including sulfur, calcium, magnesium) as well as one micronutrient (ie, manganese). Among these farmers that responded with a list of key nutrients, some talked about having their nutrients "lined up" as part of their fertility program. This approach involved keeping nutrients "in balance," such as for example, monitoring pH to ensure magnesium levels did not impact calcium availability to plants.

These farmers also emphasized that though nitrogen represented a key nutrient and was important to consider in their farm operation, tracking soil nitrogen levels was less important than other aspects of soil management, such as promoting soil biological processes, maintaining adequate soil moisture and aeration, or planting cover crops regularly. As one farmer put it, "if you add nutrients to the soil, and the biology is not right, the plants will not be able to absorb it." Or, as another farmer emphasized, "It's not about adding more [nitrogen]… I try to cover crop more too." A third farmer emphasized, that "I don't use any fertilizers because I honestly don't believe in adding retroactively to fix a plant from the top down." This same farmer relied on planting a cover crop once *per* year in each field, and discing that cover crop into the ground to ensure his crops were provided with adequate nitrogen for the following two seasons.

While most farmers readily listed key nutrients, several farmers shifted conversation away from focusing on nutrients. These farmers generally found that this interview question missed the mark with regards to soil fertility. One farmer responded, "I'm not really a nutrient guy." This same farmer added that he considered [soil fertility] a soil biology issue as much as a chemistry issue." The general sentiment among these farmers emphasized that soil fertility was not about measuring and "lining up" nutrients, but about taking a more holistic approach. This approach focused on facilitating conditions in the soil and on-farm that promoted a soil-plant-microbe environment ideal for crop health and vigor. For example, the same farmer quoted above mentioned the importance of establishing and maintaining crop root systems, emphasizing that "if the root systems of a crop are not well established, that's not something I can overcome just by dumping more nitrogen on the plants."

Another farmer similarly emphasized that they simply created the conditions for plants to "thrive," and "have pretty much just stepped back and let our system do what it does; specifically, we feed our chickens whey-soaked wheat berries and then we rotate our chickens on the field prior to planting. And we cover crop." A third farmer also maintained that their base fertility program—a combination of planting a cover crop two seasons per year, an ICLS chicken rotation program, minimal liquid N-based fertilizer addition, and occasionally compost application—all worked together to "synergize with biology in the soil." This synergy in the soil created by management practices—rather than focusing on nutrient levels—guided this farmer's approach to building and assessing soil fertility on-farm. Another farmer called this approach "place-based" farming. This particular farmer elaborated on this concept, saying "I think the best style of farming is one where you come up with a routine [meaning like a fertility program] that uses resources you have: cover crops, waste materials beneficial to crops, animals" in order to build organic matter, which "seems to buffer some of the problems" that this farmer encountered on their farm. Similar to other farmers, this farmer asserted that adding more nitrogen-based fertilizer did not lead to better soil fertility or increase yields, in their direct experience.

Regardless of whether farmers listed key nutrients, a majority of farmers voiced that nitrogen was not a big concern for them on their farm. This sentiment was shared among most farmers in part because they felt the amount of nitrogen additions from fertilizers they added were insignificant compared to nitrogen additions by conventional farms. Farmers also emphasized that the amount of nitrogen they were adding was not enough to cause environmental harm; relatedly, a few farmers noted the absurdity and added economic burden of the recent nitrogen management plan requirements—specifically among organic farms with very low N-based fertilizer application. The majority of farmers also expressed that their use of cover crops and the small amount of N-based fertilizer additions (though two farms added *no* additional N-based fertilizer) as part of their soil fertility program ensured on-farm nitrogen demands were met for their crops.

Across all farmers interviewed, cover cropping served as the baseline and heart of each fertility program, and was considered more effective than additional N-based fertilizers at maintaining and building soil fertility. Farmers used a range of cover crop species and often applied a mix of cover crops, including vetches (eg, *Vicia*) and other legumes like red clover and cowpea (eg, *Trifolium* and *Vigna*), grains (eg, *Triticale*) and cereals like oats (eg, *Avena*). Farmers cited several reasons for the effectiveness of cover cropping, such as increased organic matter content, more established root systems, greater microbial activity, better aeration and crumble in their soils, greater number of earthworms and arthropods, improved drainage in their soils, and more bioavailable N. Whereas farmers agreed that "more is not better" with regards to N-based fertilizers, farmers did agree that allocating more fields for planting cover crops over the course of the year was beneficial in terms of soil fertility.

However, as one farmer pointed out, while cover crops provide the best basis for an effective soil fertility program, this approach is not always economically viable or physically possible.

Several farmers expressed concern because they often must allocate more fields to cover crops than cash (ie, fruit and vegetable) crops in any given season, which means that their farm operation requires more land to be able to produce the same amount of vegetables than if they had all their fields in cash crops. Farmers also shared that in some circumstances, such as in early spring, they are not able to realize the full potential of a winter cover crop if they are forced to mow the cover crop early to plant cash crops and ensure the harvest timeline of a high-value summer vegetable crop. The cover crop approach to soil fertility takes "persistence," as one farmer emphasized; another farmer similarly pointed out that the benefits of cover cropping "are not always realized in the crop year. You're in it [organic agriculture] for the long haul, there is no quick fix." Indeed, farmers who choose to regularly plant cover crops to build soil fertility, rather than just add N-based fertilizers, reported that they came up against issues of land tenure and access to land, market pressures, and long-term economic sustainability.

The utility of soil testing

To build on conversations about soil fertility, farmers also provided responses to interview questions that asked them to elaborate on the usefulness of available soil tests to gauge soil fertility more broadly—and then more specifically, the usefulness of soil tests in informing their soil fertility program and/or management approaches on-farm. Overall, only three of 13 farmers reported regularly using and relying on soil tests to inform their soil fertility program or aspects of their farm operation. These farmers offered very short responses and did not elaborate. For example, one farmer shared that they "test twice a year in general," and that they "rely on the results of the soil tests to tweak [their] fertility program." Another farmer said briefly, "We use soil tests… we utilize them to decide what to do to try to improve the soil." A third farmer admitted that though he "used to do a soil test every year, literally used to spend hundreds of dollars per year on soil tests," he found that the results of soil tests did not change year-to-year and were, as he put it, very "stable." This particular farmer no longer regularly uses or relies on soil testing for their farm operation.

The remaining ten farmers confirmed that they had previously submitted a soil test, usually once (or at the upper limit for some farmers, less than five times) and most often to a local commercial lab in the region. These farmers expressed a range of sentiments when asked about the usefulness of soil tests, including disappointment, distrust, or both, particularly in the capacity of soil tests to inform soil fertility on their farm. Some farmers said directly, "I just don't trust soil tests," or "frankly, I don't believe a lot in soil testing because it's too standardized," while other farmers initially stated they had used "limited" or "infrequent" soil tests, and then later admitted that they did not use or rely on soil tests on their farm operation. These farmers tended to focus on the limitations of soil tests that they encountered for their particular farm application.

Limitations of soil tests discussed by farmers varied. Farmers stated that soil tests often confirmed what they already knew about their soil and did not add new information. For this reason, some farmers used results from a soil test as a guide, while other farmers found results to be redundant and therefore less useful to their farm operation. Because issues with soil fertility were sometimes linked to inherent soil characteristics within a particular field, such as poor drainage or heavily sandy soil, farmers found that soil tests were not able to provide new insight to overcome these environmental limitations. “I’m not able to correct that environmental limitation [ie, poor drainage] by adding more nitrogen,” one farmer emphasized. A different farmer echoed this sentiment, saying that “I’m not going to magically get rid of issues that soil tests show… I can only slightly move the needle, no matter what I do.”

Most farmers recognized that soil tests produced inconsistent results because of differences in timing and location of sampling. As one farmer noted, “You can take the same sample a couple months apart from the same field and get very different results.” Likewise, another farmer shared that, “I still struggle with the fact that I can send in two different soil tests and get two very different results. To me that seems like the science is not there.” Farmers also emphasized that each of their “fields are all so different” with “a lot of irregularity in [their] soil.” According to several farmers, soil tests did not account for variations in soil texture and soil structure, despite their observations of the influence of both edaphic characteristics on soil test results. For example, one farmer pointed out that fields that were plowed or were previously furrow irrigated created marked differences in soil test results. Similarly, another farmer shared that if a sample for soil testing was taken from an irregular patch in a field with heavier clay, differences in soil texture across samples skewed soil test results. If a systematic sampling approach was not considered, several farmers emphasized that results of soil tests might be “misleading.”

Another source of inconsistency that farmers voiced stemmed from variation in protocols used across different labs that processed soil samples. One farmer stated that in their experience, “soil tests are not really accurate, because if I use a different lab, a different person [ie, consultant] doing the soil test, it’s all different.” Several farmers also raised issues related to how well soil tests were calibrated to their type of farm. For example, one farmer pointed out that they do not use soluble forms of nitrogen, and instead relied on their animal rotations and cover crops to supply nutrients as part of their fertility program; this farmer emphasized that, “I think we need to get to a place with soil testing where it would be more applicable or be more accurately useful for a farm like mine. For example, with soil testing, if the standards you're setting, and the markers you're setting are based on farms that are putting fertilizer on the soil, I don't think my numbers are going match up. But, I can still obviously grow well in my soil.” This same farmer added that,

> My understanding is that… nitrogen comes in several different forms and the plant needs it in different forms depending on what process of its life cycle it is in. So, does there have to be that much of this particular form [of nitrogen], just because that's what most farmers dump on the soil? If that form of nitrogen isn't there in the number that we're used to, does that necessarily mean that the soil isn't healthy? I don't think so. I think the soil could be very healthy, I think our science is limited to the process that we use today.

This farmer questioned if available soil tests were calibrated to their type of farm, given that soil tests were designed for conventional agriculture (van der Ploeg et al. 1999). Several additional farmers interviewed also raised similar concerns.

Relatedly, farmers expressed that soil tests often did not match up with their own observations of their soil and fields. One farmer plainly stated, "I've had soil tests that I felt were wrong; they often do not match up with what I've observed and gathered." So instead, this farmer created a work around, "I usually just rent a backhoe every year and dig up one of my fields." Another farmer also discussed this gap in soil tests, and stated the reason for this misalignment in farmer knowledge of soil and soil test results occurred because soil tests only provided "snapshots" and that observation was "just more practical in the end" because of the historical, iterative knowledge-making farmers engage in. To this farmer, these snapshots were a "another tool" but not as powerful as direct observation; as a result, soil test results did not inform decision-making on this farm. These sentiments were often directly related to the issue of sampling discussed above.

By far, the largest limitation of soil tests that nearly all farmers (N=11) discussed related to the lack of analysis and interpretation of results provided by most commonly available tests. Farmers used a variety of metaphors to get at this general point. For example, one farmer likened using soil tests as a fuel gauge. This farmer stated that "the soil test tells me my tank is half empty, but it doesn't tell me how far you're going to be able to go... I think what's lacking from soil tests, if someone with experience [could] help me interpret the results." Another farmer wished they could ask "someone who has a lot of experience with doing soil tests—what do the results mean to you? Then I would incorporate my thoughts into the results… but there is not expertise and no dialogue." This lack of dialogue was echoed by several farmers that saw the usefulness of soil tests in the collaborative interpretation of the results. Farmers emphasized that this dialogue needed to occur not with a farm consultant, but a neutral, third party expert who could "interpret relationships." One farmer compared consultants to doctors; this farmer elaborated that,

> They [consultants] only know what they've been trained to know, based on guidelines. Like my wife, her doctor recommended going on cholesterol pills, and she says, well you can change cholesterol by adjusting your diet. You don't need a pill for that. It's a more holistic approach, rather than just adding more… I think these labs are just going through the motions.

This same farmer added that they would like to see more analysis of results, in a way that is grounded in their farm operation.

Case study: On-farm soil fertility

Farmer explanations of their selection of Field A ("least challenging" field) or Field B ("most challenging" field) were remarkably consistent across respondents. Selection of Field A was primarily based on crop productivity across all farms. Farmers also selected a field for this category because a particular field maintained good soil moisture or because a particular field did not need as much N-based fertilizer added each season compared to all other fields. Farmers also cited several reasons for selecting their low fertility fields. These fields tended to have patchy growth, low crop productivity, or in some cases, required additional N-based fertilizer to be added each season to meet production goals.

Table 3 shows a comparison of soil indicators for fertility for Field A and Field B across all farms. Ammonium concentrations were low across all farms, and ranged from 0.10 – 2.79 μg-N g-soil^{-1} for Fields A and 0.16 – 2.09 μg-N g-soil^{-1} for Fields B. Net mineralization rates were also low, and ranged from 0.08 – 1.51 μg-N g-soil^{-1} day^{-1} for Fields A and 0.05 – 1.08 μg-N g-soil^{-1} day^{-1} for Fields B. Net nitrification rates were markedly higher, and ranged widely from 1.53 – 21.45 μg-N g-soil^{-1} day^{-1} for Fields A and 2.71 – 25.18 μg-N g-soil^{-1} day^{-1} for Fields B. Nitrate concentrations were similar to values commonly found in organic agricultural systems in the region, and ranged from 2.56 – 18.12 μg-N g-soil^{-1} for Fields A and 4.46 – 23.24 μg-N g-soil^{-1} for Fields B (Bowles et al. 2015). No differences were detected between Field A and Field B among these four soil indicators.

Across all farms, total soil nitrogen ranged from 0.07 – 0.21 mg-N kg-soil^{-1} for Fields A and 0.11 – 0.23 mg-N kg-soil^{-1} for Fields B (Table 3). Total N values were significantly different between Fields A and Fields B ($p< 0.05$), with a mean value of 0.12 mg-N kg-soil^{-1} for Field A and a mean value of 0.15 mg-N kg-soil^{-1} for Field B. Total organic carbon was not significantly different between Fields A and B, and ranged from 0.77 – 2.40 mg-C kg-soil^{-1} for Fields A and 0.87 – 2.43 mg-C kg-soil^{-1} for Fields B. POXC values were in the typical range for organic agricultural systems in the region, and ranged from 225 – 707 mg-C kg-soil^{-1} for Fields A and 276 – 899 mg-C kg-soil^{-1} for Fields B (Bowles et al. 2015). Soil protein values ranged from 2.21 – 7.51 g g-soil^{-1} for Fields A and 1.86 – 8.91 g g-soil^{-1} for Fields B.

PCA indicated strong relationships among several key management variables; the results of the PCA also provided strong differentiation among farms along the first two principal components, which together accounted for 77.4% of the variability across farms (Table 4). The first principal component (PC 1) explained 55.1% of the variation, and the second component (PC 2) explained 22.3% of the variation observed across all farms. Both components had eigenvalues greater than 1.0. Additional N-based fertilizer represented the management variable most associated with PC 1—followed by tillage, and inversely ICLS. While crop diversity, cover crop frequency, and crop rotation patterns also contributed to the overall variation explained by PC 1, these management variables were weaker in comparison to N-based fertilizer additions, ICLS, and tillage. On the other hand, variables with the strongest contribution to PC 2 were crop diversity, cover crop frequency, and crop rotation patterns. Figure 1 summarizes the spatial distribution of all farms based on PCA results with PC 1 as the x-axis and PC 2 as the y-axis. As shown in Figure 3, the results of the nearest neighbor analysis order each farm from 1 to 13, and provide a basis for visualization of the gradient in management.

Therefore, this gradient in management, strongly driven by the amount of external N-based fertilizer applied on-farm, served as the basis for further visual comparison of Fields A and Fields

B across all farms (Figure 2). As shown in Figure 2a, the difference in soil ammonium concentration between fields was low (< 0.25 μg-N g-soil^{-1}) among farms on the low end of the gradient. At the middle and high end of the gradient, farms showed greater soil ammonium concentrations in Field B compared to Field A—with the exception of two farms. Farm by farm, net N mineralization rates (Figure 2c) followed trends identical to soil ammonium concentrations. Soil nitrate concentrations varied widely among farms and did not produce any consistent trends (Figure 2b); however, a majority (69%) of farms showed greater soil nitrate concentrations in Field B compared to Field A regardless of the management gradient. Like net N mineralization rates, net N nitrification rates followed trends analogous to nitrate concentrations farm by farm. For both mineralization and nitrification rates, a majority of farms (61%) showed greater rates in Field B compared to Field A, regardless of the gradient in management. Differences between Field A and Field B for total N, total C, and POXC followed identical trends farm by farm (Figure 2e, 2f, 2g respectively). Among farms on the high end of the gradient, the difference in total C between fields was consistently low (<0.3 mg-C kg-soil^{-1}). Similarly, the difference between fields in soil protein values were also consistently low (<1 g g-soil^{-1}) at the high end of the gradient (Figure 2h).

Radar plots provided further comparison of Field A and Field B across all eight indicators for soil fertility along the gradient in management developed above (Figure 3). As mentioned, because the level of N-based fertilizer input was a strong driver of the management gradient, radar plots were divided to reflect low, medium, and high N-based fertilizer inputs. Shown in Figure 3L (low input farms) is the high overlap in soil indicators, with the exception of net N mineralization and nitrification rates, between Field A and B. However, among farms with medium N-based fertilizer input (Figure 3M), the overlap of soil indicators between fields is minimal; Field B tended to show higher concentrations of soil ammonium and soil nitrate than Field A, while Field A tends to show higher values for total N, total C, POXC, and soil protein among these farms. Among high input farms (Figure 3H), differences between fields were less evident in terms of soil ammonium concentration, total N, total C, POXC, and soil protein, though soil nitrate concentrations and net N mineralization and nitrification rates did show noticeable differences in values between the two fields.

DISCUSSION

The results presented above are reflective of the perspectives, observations, and experiences of a sample of organic farmers in Yolo County, California, USA, and offer an enhanced understanding of soil health and fertility from this particular node of the organic movement (see Chapter 1). Here, we focus less, as prior studies have commonly done, on a comparative analysis that quantitatively compares farmers perception of soil health to results of soil laboratory analyses (Liebig and Doran 1999; Garlynd et al. 1994); instead, we lead the discussion with farmer knowledge of soil health and fertility, and explore emergent synergies with ongoing soil health research and soil indicator results.

Defining soil health

Establishing definitions of soil health among farmers in this study was important to gauge as a starting point to discuss soil fertility, and also for selecting fields used for soil testing. Among farmers in this case study, there was general consensus on defining soil health, with strong overlap in the particular language used by farmers.

Because farmers who participated in this study were geographically located within a significant node of the organic movement in California and many of the farmers interviewed participated directly or indirectly in the growth of this movement (see Chapter 1), the similarity in responses to define soil health suggests that—on the one hand, these farmers continue to draw their understanding of soil health from the culture and guiding principles of the organic movement to this day (Heckman 2006; Guthman 2014). Indeed, maintaining healthy soils was a central component of the organic movement, as stewardship of soil represented a direct connection to the land and a form of environmental protection (Heckman 2006; Sikavica and Pozner 2013).

At the same time, the aspects of soil health that farmers touched on here were also similar to findings by other previous studies (Gruver and Weil 2007, Guo 2021), which suggests that—on the other hand, more recent codification of the five soil health principles by the US Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) has led to widespread integration of a national soil health lexicon, as put forth by federal policy (Irvine et al. 2023). This soil health lexicon, in combination with farmers' deep cultural history with organic agriculture, likely unified definitions of soil health among farmers in this study. Interestingly, while nearly all farmers interviewed touched on the first four soil health principles in some capacity, even farmers who used integrated crop livestock systems (N=7) did not explicitly mention the importance of livestock integration (Soil Health Principle #5, USDA-NRCS, 2012). This finding suggests that perhaps due to sensitivity around food safety concerns, farmers may not openly emphasize livestock integration in conversation, because although this practice may be considered beneficial to their soil, in reality, they face structural and policy limitations (Baur 2022).

The relative importance of soil indicators for fertility

Despite the emphasis on understanding nutrient cycling and nitrogen availability to crops in soil health research and fertility management (Cappellazzi and Morgan 2021), we found that for most farmers interviewed in this study, tracking nutrient levels was less important than other aspects of fertility management. Moreover, for these farmers, managing for soil fertility required a holistic approach that went beyond understanding nutrient levels. Farmers also underscored that measuring indicators for soil fertility (eg, nutrient levels, such as total soil nitrogen or soil inorganic nitrogen) was not particularly useful to maintaining soil fertility in practice, because assessment of soil indicators lacked integration with management practices. In most farmers' experiences, assessing soil indicators was often associated with prescriptive (ie, adding more nitrogen-based fertilizer) rather than holistic (eg, applying more cover crops in the farm rotation, maintaining soil structure, etc) solutions. In this sense, farmers stressed that the synergy of multiple management practices over space and time guided their approach to building and assessing soil fertility on-farm, rather than using soil nutrient levels as a guide—a key finding that is also emerging in recent literature (Irvine et al. 2023).

While farmers agreed that gauging soil nitrogen and other key soil nutrients was important to consider and be aware of generally, other aspects of soil management, such as promoting soil biological processes, maintaining adequate soil moisture and aeration, or planting cover crops in regular rotation, were more critical to adequately maintaining soil fertility on their farm. An analogous soil health study similarly found that among predominantly non-organic farmers in the midwestern part of the US, measuring nutrient levels in soil was generally not highlighted by farmers interviewed (Gruver and Weil 2007). When prompted to discuss key aspects of soil health, a majority (63%) of farmers in this past study completely omitted mention of the importance of gauging nutrient levels, or in their case "soil mineral fertility," as an indicator for soil health. This prior finding in combination with our findings here suggests that measuring nutrient availability to crops may not be as important as initially hypothesized to organic and non-organic farmers alike. Importantly, Gruver and Weil (2007) posited that the lack of emphasis on soil mineral fertility among these midwestern farmers may have occurred because they perceived that their soil fertility was not currently limited by nutrient availability to crops. Our research with organic farmers in California corroborates this hypothesis, and we suggest further research in other farming contexts to see if this sentiment among farmers is more widespread.

We learned that there were three related reasons for why organic farmers in our study expressed that measuring nutrient levels was not particularly relevant for gauging soil fertility on their farm operation. For one, as already mentioned, farmers emphasized that they relied on carefully orchestrated soil management practices—such as the application of cover crops and livestock rotations—rather than depending on organic nitrogen-based fertilizers—to supply nutrients to crops. Because a majority of farmers (N=8) applied less than 25 kg-N/acre (with five of 13 farmers applying <2 kg-N/acre) of additional fertilizer per growing season, farmers in this context emphasized that their soil chemical and biological processes related to soil fertility may potentially diverge from agriculture that was predominantly or exclusively fertilizer-based. By creating internally regulated farming systems via diverse management practices, these farmers observed that in general nutrient availability to their crops was ensured over the growing season.

This key finding shared by farmers overlapped strongly with hallmarks for resilient agriculture outlined by Peterson et al. (2018), who summarized features of internally regulated farming systems and key management practices associated with these systems. Based on knowledge shared by farmers, we suggest that it is possible for farming systems that integrate multiple management practices rather than rely on external fertilizer inputs to create soil conditions that "buffer" soil nutrient levels. In these internally regulated systems, measuring nutrient availability to crops may be less practical or even achievable with available soil indicators, as certain nutrients (eg, nitrogen) only become available as needed by local soil processes, and strongly depend on plant root structure, associated mycorrhizal pathways, and microbial communities present (Hartmann and Six 2022; Cavagnaro et al. 2015; see Chapter 2).

To this end, several farmers hypothesized that available soil indicators were not sensitive to alternative approaches to maintaining soil fertility, likely because these fertility management practices operated on different timescales of nutrient release compared to direct fertilizer application. These conclusions drawn by farmers on the limits of measuring nutrient availability to crops were not unlike broad thematic gaps in measuring bioavailable nitrogen to crops discussed by Grandy et al. (2022) and others previously (Müller and Clough 2014; Daly et al. 2021; see also, Chapter 2). In particular, Grandy et al. (2022) discussed the importance of considering soil health gradients, especially on farms that are not "ecologically simplified" and do not rely extensively on fertilizer application; such farm systems, like the farms examined in this study, are not as dependent on soil inorganic N and instead rely on what Grandy et al. (2022) call "a highly networked supply of organic N." In other words, as farmers in this study also pointed out in interviews, soil health and fertility depend on a variety of factors, such as plant root accessibility, the microbial communities present, and soil mineral properties (Jilling et al. 2018). As hypothesized in recent soil health literature, available soil indicators may not fully capture the complex plant-microbe-soil interactions that regulate fertility, particularly on organic farms that use minimal organic fertilizer application—a sentiment supported by farmer knowledge in this region as well.

Second, farmers in this study also questioned whether available indicators for soil nutrient levels were calibrated not only to alternative farming approaches but also to local soil conditions. Farmers emphasized that soil test metrics were not grounded in their farm operation and produced inconsistent results that were likely due to a combination of spatial and temporal variations in their land, and also due to differences in inherent soil characteristics. As most farmers also pointed out, soil indicators for fertility did not explicitly calibrate for inherent soil characteristics, such as soil structure and soil type, or soil management history. Yet, to farmers, local knowledge of prior and ongoing soil management were integral to making management decisions that improved, or at least maintained, soil fertility on their farm.

Farmers in this region stressed that the synergy of management practices they applied were often calibrated to account for physical soil variability among fields, and therefore were closely informed by their local soil conditions and unique management histories. While the importance of considering soil aggregate stability, soil texture, and management history when assessing soil indicators is well-documented in the soil health literature (Bagnall et al. 2023; Sprunger at al. 2021; Williams et al. 2020; see Chapter 2), in practice there continues to be a gap in soil health indicators that are tailored to be site-specific and/or farming system relevant (Wander et al. 2019). Given that soil indicators can vary by region and soil type, farmer involvement to provide key knowledge of local soil necessary for calibration of soil indicators is one essential way forward toward closing this gap. Merging results of soil tests with farmer knowledge may also help to increase sensitivity and utility of soil indicators across varying local soil contexts.

Relatedly, farmers agreed that finetuning management could alleviate (but never undo nor overcome) challenges associated with inherent limitations due to physical soil characteristics (eg, patches of soil with heavy clay, poor soil drainage, etc). Local farmer knowledge from this study established that inherent limitations posed by their soil or poor prior management (eg, working the soil when too wet) could not be overcome by adding more N-based fertilizers—even if soil indicators showed the contrary. Interestingly, prior studies in the region found that organic fertilizer use in the early organic movement was potentially more widespread. For example, early organic farmers in Yolo County who were interviewed by Guthman et al. (2014) in the early 1990s used high nitrogen-based organic fertilizers such as pelleted chicken manure, seabird guano, and Chilean nitrate to supply fertility to soil in their organic production; based on interviews here, several decades later, farmers appear to have significantly cut back on the use of such high nitrogen-based organic fertilizer products. Several of these farmers have explicitly realized that "more is not better" when it comes to organic fertilizers; as discussed above, the majority of farmers interviewed here have shifted towards implementing a synergy of management practices that promotes good soil structure, increased soil microbial activity and soil organic matter, and adequate soil moisture rather than using high nitrogen-based organic fertilizers.

Third, these organic farmers unanimously agreed that soil test results could be more useful to them if the numerical results were also provided with meaningful interpretation, ideally in the form of a direct conversation—and that importantly, moved beyond prescriptive recommendations for nutrient additions (or nutrient re-balancing) and organic fertilizer application. Farmers interviewed used a variety of rich metaphors to elaborate on this point, such as likening soil test results to the fuel gauge in a car; both provide little insight into the actual mechanics of how well the *system*, be it an engine or a soil ecosystem, is actually functioning. This key takeaway from farmers in this study suggests that available soil indicators do not fully account for the complexity of their ecological farming systems, and that farmers see the interpretation of soil test results as an essential part of addressing the underlying complexity, and holistic soil function in their broader agricultural ecosystem. Our study provides an initial window into farmer knowledge of soil function in relation to soil fertility; however, as Petrescu-Mag et al. (2020) emphasize, deeper research on this particular gap in farmer knowledge of soil function is essential to determine the specific content of interpretations accompanying soil test results that would be practical and informative to farmers.

Another potential way to bridge this gap in applicability for farmers would be to incorporate descriptive indicators for soil fertility in conjunction with available quantitative soil indicators. As Romig et al. (1995) suggested several decades ago, descriptive indicators can integrate well with existing soil metrics, and therefore provide mutually acceptable alternatives to discuss soil health and fertility among farmers and scientists alike. Finding a common language through which to engage is at the heart of this current gap in soil health research (De Bruyn and Abbey 2003).

Soil fertility indicators in practice

Indicators for soil fertility measured here provided limited effectiveness in differentiating between fields deemed by farmers as “most challenging” (in terms of maintaining soil fertility) and “least challenging” (in terms of maintaining soil fertility), which suggests that current scientifically developed metrics for measuring soil fertility do not align well with farmer developed benchmarks for soil fertility. This outcome additionally suggests that nutrient availability was not the driving factor for farmer perceptions of soil performance, at least in terms of soil fertility.

Of the eight indicators for soil fertility measured in this study, total soil nitrogen was the only indicator that was able to detect differences in soil fertility (Table 3); *however*, fields selected by farmers as “most challenging” showed on average higher values of total soil nitrogen than fields selected by farmers as “least challenging.” Because higher total soil nitrogen values are generally equated with higher soil fertility in the soil health literature, we hypothesized that the “least challenging” fields would show on average higher values of total soil nitrogen (see Chapter 2). This alternative outcome here suggests that while this soil chemical property (ie, total soil nitrogen) shows sensitivity to differences perceived by farmers in their selected fields, this commonly used indicator does not adequately capture the direction of farmer knowledge of soil fertility between their selected fields. On the one hand, it is not surprising that total soil nitrogen was the only soil indicator able to detect differences between farmer-selected “most challenging” and “least challenging” fields, especially given that after nearly a century of research total soil nitrogen remains one of the most predictive measures of soil fertility status (Grandy et al. 2022). However, the contradictory direction of our results for total soil nitrogen between farmer-selected “most challenging” and “least challenging” fields emphasizes that current scientific application of this soil indicator does not readily transfer for use on-farm.

One potential reason for this inconsistency may be because as a soil indicator, total soil nitrogen reflects both the amount of chemically stable organic matter and more active organic matter fractions, and therefore gives a rough indication of nitrogen supplying power in the soil. However, in practice it is possible that fields deemed by farmers as “least challenging” have depleted their nitrogen supplying power due to more frequent crop plantings, for example—compared to fields that are “most challenging” and therefore may be less frequently planted with crops throughout the year. This finding underscores the current lack of (but also simultaneous importance of) interpretation of soil test results in community with both agricultural researchers and farmers present together; the current gap in interpretation of soil testing results was repeatedly emphasized by farmers during interviews, and suggests that—moving forward, contextualizing and interpreting soil test results in local farming contexts is key to disentangling potential mismatches between farmer knowledge systems and agricultural researcher knowledge systems. To move toward this outcome requires deep listening and relationship building on the part of agricultural researchers not currently widely applied (Kearns 2012).

Whereas another similar study found that active carbon (permanganate-oxidable carbon, or POXC) was the singular most sensitive, repeatable, and consistent soil health indicator able to differentiate between fields in their study on organic farms in Canada (Hargreaves et al. 2019), we highlight that one potential reason for this difference in our results might be as a result of differences in management in each study. While our study consisted of farms along a gradient of organic management (Figure 1), the prior study focused on three organic farms with similar management. This divergence in results highlights the importance of accounting for a gradient in management when evaluating the efficacy of soil health indicators on working farms. Much remains to be learned about how inherent soil properties and dynamic soil processes interact with complex management systems on working farms (Karlen et al. 2017).

Limited prior research that has looked at the effects of multiple soil management practices indicates that metrics for soil health are a product of both inherent soil properties and dynamic soil properties (Williams et al. 2020). Whether available soil indicators could translate these soil properties and processes when management systems are complex remains unclear. As an added layer of complexity, field variability (eg, due to microsites or uneven soil type) is hard to distinguish from management-induced changes in soil properties (Beehler et al. 2017). To address this challenge, prior studies have suggested increasing samples, the number of sites, and sampling strategies that account for spatial and temporal variability (Karlen et al. 2019); however, as farmers themselves expressed in this study, such an approach requires additional time and resources, and may not increase their utility—at least to farmers—in the end. In this sense, farmer knowledge may serve as an important mechanism for ground-truthing soil health assessments, particularly when management is synergistic and does not rely heavily on organic fertilizers. As emphasized by our results above, farmer involvement in soil health assessment studies is imperative to better converge soil indicators with farmer knowledge of their soil.

Lastly, our results also highlight the utility of incorporating information about nitrogen-based fertilizer application on sampled field sites, particularly when assessing soil indicators on working farms with a large variation in the quantity of N-based fertilizers applied (Figure 3). Farms on the low end of additional organic fertilizer application (< 2 kg-N/acre) showed minimal differences between farmer selected fields for soil fertility, particularly in terms of soil inorganic nitrogen (ie, soil ammonium and nitrate concentrations)—which suggests that differences in soil fertility in fields with more circular nutrient use may be less detectable using commonly available soil indicators. This cursory finding here corroborated farmer observations touched on in the previous (Discussion) section above, and requires further investigation to see if similar trends extend to other organic systems.

CONCLUSION

Here, we have identified several gaps in the utility of commonly available indicators for soil fertility among a unique group of organic farmers in Yolo County, California using interviews with farmers and field surveys. Our study highlights that if available soil indicators are to be considered effective by farmers, they must be grounded in farmers' realities. Moving forward, working in collaboration with farmers to close this continued gap in soil health research will be essential in order to ground widely available soil indicators in real working farms with unique management systems and variable, local soil conditions. This approach is particularly needed among organic farms that do not rely extensively on nitrogen-based organic fertilizers and additional nutrient input to supply their fertility, as available soil indicators do not adequately reflect farmers' descriptive metrics for soil fertility. Moreover, our research elevates concerns that currently available soil indicators used in soil health and fertility assessments may not fully capture the complex plant-microbe-soil interactions that regulate soil fertility, particularly on organic farms that use minimal organic fertilizer application. Moving forward, additional studies that pursue a deeper dive into nutrient dynamics across a gradient of management and varying nitrogen-based fertilizer input is needed.

Overall, the strong overlap between farmer knowledge in this study and ongoing soil health research speaks to the opportunity to further engage with farmers in developing useful indicators for soil health and fertility that are better calibrated to local contexts and draw on local farmer knowledge. A deeper investigation of farmers knowledge systems, in particular farmer understanding of soil function in connection with crop productivity, soil health, and soil fertility, represents a critical path forward for this research arena. Additionally, we recommend placing greater emphasis on developing descriptive indicators for soil health and fertility in collaboration with farmers that are better integrated with ongoing qualitative soil health and fertility metrics. These descriptive indicators should not be developed in isolation to ongoing research on soil health and fertility assessment, but rather as an integrated research process among scientists, farmers, and extension agents—importantly, with scientists as listeners working toward a shared language.

TABLES

Table 1. Profile of each farm including farm size (total acres), total crops per season at the whole farm level, soil texture class for Field A and Field B, specific crops in Field A and Field B at the time of field sampling (summer of 2019), the type and amount (in lbs/acre and kg-N/acre) of N-based fertilizer applied at the farm level, and key aspects of soil health for each farmer. OM refers to organic matter.

Farm	Farm Size	Total Crops	Soil Texture Class		Crops in Field (Summer 2019)		**Fertilizer Application (Summer 2019 Season)**			**Key Aspects of Soil Health**
	Acres	Per season	A	B	A	B	Type	lbs/ acre	kg-N /acre	From farmer
1	26	50	Clay Loam	Clay Loam	Summer squash, pumpkin, melon, cucumber, basil	Tomato, basil, sunflower	N/A	0	0	Promote soil respiration & soil life Maintain moisture in soil Limit soil compaction
2	15	10	Loam	Loam	Tomato	Summer squash, melon, cucumber	Fish Emulsion (5%-N)	10	0.25	Promote soil life Maintain crop health & vigor
3	100	50	SCL	SCL	Tomato, onion, turnip, kale	Strawberry	N/A	0	0	Maintain moisture in soil Keep soil alive Minimize soil disturbance Maintain diversity
4	22	10	Loam	Loam	Tomato, pepper, cucumber, summer squash	Sunflower, safflower	Fish Emulsion (5%-N); Liquid Wiserg (3%-N)	2; 18	0.30	Monitor crop health Keep soil alive Promote diversity Work with nature No external inputs

5	200	35	Clay Loam	Clay Loam	Tomato	Tomato	Liquid Wiserg (3%-N)	145	2	Promote good drainage Limit external inputs Monitor crop health Prevent pest and disease issues
6	350	50	Loam	Loam	Summer squash, cucumber, basil	Summer squash, beans, corn	Liquid Wiserg (3%-N)	200	2.75	Limit soil compaction Never work ground wet
7	450	40	Loam	Clay Loam	Onion	Leek, celery root, pepper	Liquid Wiserg (3%-N); Pelleted Chicken Manure (4%-N)	200; 500	12	Focus on building OM Enhance microbial & fungal activity Maintain soil structure Minimize soil disturbance
8	40	35	Loam	Loam	Tomato, pepper, summer squash, tomatillo, eggplant, onion	Tomato, melon	Liquid Wiserg (3%-N); Pelleted Chicken Manure & Feather meal (5%-N)	60; 1,000	24	Maintain soil life Maintain moisture in soil Promote good drainage Examine crumble of soil, earthworms, aggregates Minimize soil disturbance
9	17	3	Loam	Loam	Tomato	Summer squash	Liquid Wiserg (3%-N); Pelleted Chicken Manure & Feather meal (5%-N)	200; 4,000	94	Maintain good soil aeration Promote looseness of soil Monitor crop health Enhance soil life

10	700	40	Loam	Loam	Pepper, squash, beans	Onion	Pelleted Chicken Manure (4%-N)	6,000	110	Build organic matter Limit pests and disease
11	800	6	Loam	SCL	Seedless watermelon	Summer squash	Seabird Guano (12%-N); Pelleted Chicken Manure (4%-N)	450; 6,000	135	Enhance soil life Maintain capacity of soil to adapt
12	500	10	Clay Loam	SCL	Tomato	Safflower	Seabird Guano (12%-N); Pelleted Chicken Manure (4%-N)	450; 8,000	170	Maintain good earth smell Minimize disturbance
13	800	12	SCL	Clay Loam	Beet	Safflower	Pelleted Chicken Manure (4%-N)	10,000	180	Maintain crop health and vigor Limit pests and disease

Table 2. Farmer responses to the question – "To what extent, and in what way, do you think about key nutrients—in terms of soil fertility—on your farm? How do you manage for soil fertility? What does your soil fertility program entail?" (Column 2), and a follow up question – "Do you use soil tests? How useful, or not, are soil tests to you and your farm operation?" (Column 3). Keywords to describe general farmer ethos (Column 4) are listed to summarize and code farmer ethos of soil fertility.

Farm	Nutrient & soil fertility management	Soil tests	Keywords
5	I'm not really a nutrient guy. Our soil tests show that nitrogen is our biggest issue here, period. Our second biggest issue is calcium and magnesium. I consider that a soil biology issue as much as a chemistry issue. The only time we really have to worry about nitrogen is during a drought year, when we don't get enough rain in the wintertime to flush all the nutrients down. Because of all the compost we have high levels of phosphorous and potassium, too high. That's one reason not to rely on compost for all your fertility. One of the ways I manage crop fertility is by using furrow irrigation for crops, because I feel like you give your plants better access to the full soil nutrients in their profile by furrow irrigation. I feel like we can get a better nutrient response. If the root systems of a crop are not well established, that's not something I can overcome just by dumping more nitrogen on the plants.	I just don't trust soil test. I've had soil tests that I felt were wrong; they often do not match up with what I've observed and gathered. I feel that most nutrient issues that we have are related to problems with the soil that I'm not able to correct. Or environmental limitations. For example, right now, the soil is too cold and biological processes slow down so the crops are just not getting enough nitrates. Going out there and top dressing all those fields is not going to fix that problem. It's just something you have to be patient with and wait. Or, often soil tests just confirm what you already know. There is one field that as a drainage issue and I'm not going to be able to overcome that by adding more nitrogen. Instead, I usually rent a backhoe every year and dig up one of my fields. For example, the soil maps say there is a clay pan down 40 inches, but we checked, and most of this area does not have a clay pan actually. We have found areas with a perched water table that has poor drainage, so that is interesting.	Building the plant root system; importance of management; against fertilizer application; holistic approach; distrust in soil tests
2	There's a lot that can be done. You've got to get your macronutrients lined up so they are balanced: nitrogen, phosphorous, potassium, sulfur, calcium, magnesium. Here, Magnesium is pretty high which makes getting the calcium into the plant harder and this drives pH up. I've had amazing results with foliar	I test twice a year in general. I rely on the results of the soil tests to tweak my fertility program.	Building the plant root system; importance of management; pro-fertilizer application; piecemeal and

	feeding, especially keeping Fusarium down with adding manganese. When you add nutrients to the soil, you really need the biology to cooperate to get things into the plant. If you add nutrients to the soil, and biology is not right, the plants will not be able to absorb it. I am hoping that I can get the soil biology to recover which would help with maintaining healthy nitrogen level in my crops. This all needs to happen around crop planting not during the season.		formulaic approach; trust in soil tests
12	I usually apply more nutrients as a "seasoning." I use bat guano; I want the high nitrogen fertilizers. I think about nitrogen and phosphorous, and also sulfur and calcium. My fertilizer inputs on all my organic fields are not dosed up like on the conventional fields. But, the soil test results, NPK, are about the same for both. So it's not about adding more [nitrogen]… I try to cover crop more too.	I consider the results of a soil test. But if I go by the results of the soil test, the consultants always want me to put more on my fields, and it's just not cost effective for me. There are other ways to achieve this, like cover crops. Soil tests are just a guide. The soil is only going to tell you so much, and the consultant is only going to tell you so much. I'd like to see more analysis of the results. I think all these labs are just going through the motions; they know how to test and do the results, but to analyze the results is a different story. Consultants are like doctors, they only know what they've been trained to know, based on guidelines. Like my wife, her doctor recommended going on cholesterol pills, and she says you can change cholesterol by adjusting your diet. You don't need a pill for that. It's a more holistic approach, rather than just adding more.	Nutrients as seasoning; minimize fertilizer application; holistic approach; soil tests as guides
9	We have to make sure we have enough nitrogen but not too much nitrogen at the wrong time. Compost helps soften the ground. It helps microorganisms in the soil build up. We add a little sulfur. We add pelleted chicken manure. Sometimes we add oyster shells.	We had a consultant from one of the fertilizer companies come out and send in some soil tests. But the company has changed, as it got bought. We rarely soil test. I want to know what other things we should be doing or adding, perhaps a farm advisor would be better for this than a soil test.	Pro-fertilizer application; piecemeal and formulaic approach; trust in soil tests

4	I am now required by law to do nitrogen balancing, from the local water coalition. I have a nitrogen plan and a sediment plan. The nitrogen plan has to be done by a certified nitrogen planner. So I took the course to become a certified planner so I could do my own plan. My plan consists of growing cover crops and that's about it. I am sure that the cover crops that I grow put more nitrogen into the ground than is removed from the vegetables I grow. I had compost from time to time. I don't add extra fertilizer; whatever the cover crop is doing, I am fine with that.	The only soil test that I have done is only once, just 4 years ago. I just did it once. I decided to try it on a whim. I got the bare bones test, pH and a few different nutrients. They gave some recommendations. It was useful to learn, but it was all what I kind of already knew. The results are so sensitive to how you sample. Because there is a lot irregularity in my soil, like where stuff got plowed or where there used to be a furrow, I don't have a good sense of how to sample with all this in mind. Samples might be misleading for this reason.	Importance of management; against fertilizer application; holistic approach; distrust in soil tests
8	There are the five big ones: nitrogen, phosphorous, calcium, and sulfur. Nitrogen I'm not worried about, because we supply nitrogen with organic blended nitrogen fertilizers, although I'd much rather supply it with cover crops. If I can get a cover crop in every couple of years, that is ideal. But, I buy nitrogen mainly in the form of chicken manure. From a conventional point of view, we're not even putting on a fifth of the amount of fertilizer they do. By the time I add up all the nitrogen we use, we are at like 50 lbs of nitrogen per acre, which is one fourth to a half of what you're supposed to have to a grow a crop, according to fertilizer companies. And yet, everything seems to do OK. So I'm not really concerned about nitrogen.	We used to test, every three or four years or so. I would go around and gather 8 or 9 samples. The fields are all so different and we grow different crops in them, so I can't just go out and say this is it for the whole forty acres. I pick the plots that grow important crops. I used to do a soil test every year, literally used to spend hundreds of dollars per year on soil tests. I found there was not much difference year to year, really. We would send them down to the lab to see if anything was shifting over time, but I found that generally not. Soil test results are very stable and that is why I don't do it anymore. As long as I don't abuse the ground, the soil nutrients will stay where they need to be, so soil tests can't really tell me more than I already know from previous soil tests. They're not very sensitive.	Nutrients as seasoning; pro-fertilizer application; piecemeal and formulaic approach; soil tests as a guide
1	Nitrogen, calcium, sulfur, phosphorous. A little but about magnesium, because it's required to balance calcium. Micronutrients I don't worry about much. I mean we have birds flying around that drop feathers, deer and turkey that drop manure. In terms	I couldn't tell you the last time we did a soil test, maybe 20 years ago? I would really like to engage with someone who has a lot of experience with doing soil tests, and ask "What do the results mean to you?" Then have a discussion about that; and if	Building the plant root system; importance of management; against fertilizer

	of estimating nutrient balancing, I do this poorly. I just figure if I add compost to my cover crop plants, and if I cover crop once a year, that works. I gauge nutrients based on the growth of the cover crop. If I see a good growth of the cover crop, then know that everything is in balance. I know that when I disc in that cover crop, there will be a downturn in fertility for a few weeks, but if I wait, the ground will recover and nutrients will start to be released. Then I can add some compost if needed, and incorporate that. I don't use any fertilizers because I really honestly don't believe in adding retroactively to fix a plant from the top down. If I've done something wrong, I'd rather follow that through and see what happens, and try to figure out what I did was wrong in preparing the soil for a good crop. I strongly believe to have a healthy plant, it's necessary to have a healthy soil. I don't believe that you can spray your way to a healthy plant.	we did that, then I would incorporate my thoughts into the results, and share my practices; for example, this is how these practices show up in a soil sample at this point in time. But there is not expertise and no dialogue, so soil tests are just not useful.	application; holistic approach; distrust in soil tests
13	The biggest are the three: nitrogen, phosphorous, and potassium. Calcium is one nutrient we look at. In terms of nutrient balancing, I rely on research available from the university, mainly, and from experience over the years. But most of that eventually comes from research. If you're working on soil that has not been rotated and managed well, you might get a good response from adding nutrients. We generally use compost and cover crops, but we don't really add any additional fertilization beyond that. Mostly because they are extremely costly.	We use soil tests; they are useful. We know they're pinpointed and aggregated, which creates limitations, but we utilize them to decide what to do to try to improve the soil.	Importance of management; pro-fertilizer application; piecemeal and formulaic approach; trust in soil tests
7	I think a lot about nutrients. Nutrient management is a huge one. In organic systems, we generally have a hard time getting nitrogen to plants. We just don't	We do some infrequent soil and petiole sampling. I still struggle with the fact that I can send in two different soil tests and get two very different results.	Building the plant root system; importance of

	have the same resources that the chemical fertilizer affords. Most of it is insoluble, and even the soluble nitrogen is at levels much lower than you see in conventional. On our farm, we gauge soil fertility mostly through observation. Nutrient management is crop specific, some crops needs more, some crops need less. But we do apply compost, then side dressing or fertigating (ie, compost tea fish-based or seaweed-based through irrigation systems), which is not a heavy nutrient supplement, just expensive. Most of the time, this year's plants are actuating last year's application.	To me that seems like the science is not there. So with that said, testing is just another tool. The soil test analyses that are provided with results rank samples very differently from my experience, or my own analysis, my own understanding. Soil tests are snapshots, right? I think if soil tests were done in a more formidable way, with a series of snapshots and a lot of repetitive sampling. But then again, I don't see the need or the return on that. Observation is just more practical in the end.	management; pro-fertilizer application; holistic approach; soil tests as a guide
3	We really don't balance nutrients; we have pretty much just stepped back and let our system do what it is does. Specifically, we feed our chickens whey soaked wheat berries and then we rotate our chickens on the fields prior to planting. And we cover crop.	The last soil test we did was about 10 years ago. We figured at the end of the day, why are we doing this? It's more important for me to see what is actually happening to the crops. I have been thinking about doing a soil test, just out of curiosity to get a baseline idea. But I am skeptical because I think soil tests need to improve where they are more applicable to a farm like mine. Plus, if I had soil testing done, and I looked at the numbers, I don't really know how relevant it would be to my farm; what would it tell me that I can actually implement on my far? I'm not going to just dump nitrogen on my soil, like the conventional farmers next door.	Building the plant root system; importance of management; against fertilizer application; holistic approach; distrust in soil tests
6	We are always thinking about nitrogen to a certain extent, but not as much as one would think. Our base fertility program tends to keep enough nitrogen mineralizing that if you have enough soil biology going on, the plants will find nutrition. We're all required to do a nitrogen management report, for the state, which is another two days of waste every year. We just don't have the ability to put on enough nitrogen to create runoff as organic farmers, unless	We do limited soil testing to see what's going on in the soil. You can take the same sample a couple of months apart from the same field and get very different results. So I feel like soil tests are less useful than they should be. Soil sampling tells me less than I wish it did. I wish it could tell me more about soil microbiology and the relationships between all the nutrients. There are relationships there among the nutrients that I just don't understand very well. But I	Building the plant root system; importance of management; pro-fertilizer application; holistic approach; distrust in soil tests

	you are doing some crazy input-substitution program. We're doing mostly the same thing on all our soils, which is we are cash cropping less and cover cropping more. Beyond crop rotations, occasionally adding compost, the chicken rotation program, we do add a liquid nitrogen fertilizer on drip, which helps synergize with biology in the soil. I think keeping your bulk tillage to a minimum so you're not just burning up all your organic matter.	think having a good cover crop always enhances the results of the soil test.	
11	We use spreadsheets out here to evaluate all our fields and the soil. You may be looking at say, pelleted blood meal; it's 16% nitrogen. Then you look at the price. Then you look at another material and it's cheaper, only $200 per ton but it's only 3% nitrogen. How much am I paying per pound of nitrogen? The price of nitrogen compared to the cheap stuff was actually less, because the cheap stuff is like buying a donut. You're not getting any nutrient out of it. I use the best scientific wisdom that is out there as a resource and go from there. The problem with cover cropping and composting is that it's not always realized in the crop year. So that's why I think with organic agriculture, you're in it for the long haul, there is no quick fix. I never save money on fertility. It's not one of my budget cutting points. We even fertilize our cover crops! We broadcast compost before we plant our cover crops because then the cover crops can do their best job in a short period of time. So we make it easy for them so they can produce more biomass that goes right back into the soil.	Frankly, I don't believe a lot in soil testing because it's too standardized. It is going to tell me what the relationships mean? I think what's lacking from soil tests, if someone with experience helping me to interpret the results. Because I don't understand all the relationships, like between magnesium and calcium, and how certain nutrients are bound up, and how you can lower pH. Those kinds of questions are beyond my expertise, and so someone with a greater understanding of agronomy that is able to make good interpretations. I use soil tests as a fuel gauge. The soil test tells me my tank is half empty, but it doesn't tell me how far you're going to be able to go. But even then, soil tests are not really accurate, because if I use a different lab, a different person doing the soil test, it's all different. Testing the plants is more valuable because it's telling me what's going on in the plant. I would say soil tests would be more useful if there was a narrative attached to each one. If I ask my friend who is a soil scientist, he says it could be this, or this or this. If I ask a consultant, he'll say you need more of this, or more of that. That's when the doctor is trying to sell you something. So we need a third party, someone neutral to help interpret	Nutrients as seasoning; pro-fertilizer application; piecemeal and formulaic approach; distrust in soil tests

		relationships and what “could be” things we need to be paying attention to.	
10	Nitrogen always comes to mind. Calcium. Part of me thinks, maybe I should stop adding all this extra nitrogen and see what happens. I bet you my yields would be the same. Because I’ve never really seen a true correlation between “more is better.” But I also inherently know that I’m removing nutrients with each season, so to not put something back would be silly. I think the best style of farming is one where you come up with a routine (meaning like a fertility program) that uses resources you have: cover crops, waste materials beneficial to crops, animals. The hard part is gauging if the output is enough, because it’s tied to capitalism. For example, would it be smart of me to buy a bunch of Chilean nitrate and bat guano, and see if my yields go up 20%? If it does, does that mean what I’m doing is now wrong? It get very philosophical quickly. So, I’m place-based in my thinking about nutrients. I’m trying to minimize what I add to my fields. The main strategy for me is to continue to build organic matter. It seems to buffer some the problems. Cover cropping is key.	Farming is surprisingly predictable. I’m not going to magically get rid of the issues that soil tests show. I’m not magically going to create new issues either. Soil testing just helps to show some of the problems I have in my soils; I can only slightly move the needle, no matter what I do.	Nutrients as seasoning; importance of management; minimize fertilizer application; holistic approach; soil tests as a guide

Table 3(a) and (b). Comparison of Field A and Field B across all farms for eight indicators for soil fertility, including soil ammonium and soil nitrate concentrations, net N mineralization and nitrification rates, total soil nitrogen and total organic carbon, POXC, and soil protein. Significant ANOVA results ($p<0.05$) are highlighted (*).

(a)

Farm	**Ammonium** µg-N g-soil^{-1}				**Nitrate** µg-N g-soil^{-1}				**Net Mineralization** µg-N g-soil^{-1} day^{-1}				**Net Nitrification** µg-N g-soil^{-1} day^{-1}			
	A	se	B	se	A	se	B	se	A	se	B	se	A	se	B	se
1	1.05	0.01	1.20	0.14	10.07	0.05	8.32	0.26	0.38	0.030	0.59	0.084	3.53	0.34	1.52	0.56
2	0.99	0.06	1.23	0.13	4.73	0.22	14.79	1.25	0.11	0.021	0.63	0.147	1.31	0.31	18.21	2.57
3	2.38	0.23	2.40	0.17	11.96	0.76	27.08	1.64	1.27	0.032	1.33	0.083	8.53	1.25	19.45	0.66
4	1.28	0.08	1.16	0.07	21.29	1.46	9.17	0.25	0.19	0.012	0.16	0.073	15.44	0.61	6.21	0.69
5	0.25	0.08	0.22	0.05	2.95	0.20	5.37	0.15	0.29	0.104	0.07	0.007	2.60	0.35	2.71	0.09
6	1.08	0.05	2.64	0.20	9.73	0.63	18.92	0.54	0.05	0.004	1.15	0.007	3.29	0.46	15.98	0.46
7	0.10	0.04	1.15	0.03	10.85	0.24	22.82	1.39	0.42	0.019	0.52	0.027	5.92	0.95	7.97	0.01
8	1.05	0.01	0.16	0.01	8.36	0.65	11.27	0.45	0.07	0.069	0.03	0.014	2.60	0.15	7.56	0.32
9	0.93	0.01	1.16	0.09	3.49	0.22	8.97	0.32	0.74	0.032	1.46	0.127	2.34	0.41	6.13	0.43
10	0.91	0.04	1.95	0.05	2.56	0.59	4.81	0.53	0.15	0.003	0.49	0.066	1.98	0.26	3.46	0.17
11	0.31	0.04	1.43	0.04	10.43	0.71	8.29	0.14	0.10	0.019	0.69	0.077	1.69	0.01	7.37	0.02
12	0.21	0.03	0.30	0.07	5.27	0.16	6.72	1.05	0.22	0.060	0.51	0.006	3.16	0.51	3.55	0.14
13	2.79	0.05	1.39	0.09	20.11	1.93	11.89	1.17	1.51	0.139	0.60	0.041	14.10	1.20	12.32	0.86

(b)

Farm	Total N* mg-N kg-soil^{-1}				Total C mg-C kg-soil^{-1}				POXC mg-C kg-soil^{-1}				Soil Protein g g-soil^{-1}			
	A	se	B	se	A	se	B	se	A	se	B	se	A	se	B	se
1	0.17	0.009	0.23	0.012	2.40	0.240	2.43	0.181	707	41	826	34	7.5	0.4	7.0	1.0
2	0.11	0.018	0.21	0.003	1.80	0.285	2.26	0.176	673	29	899	83	6.9	0.8	8.9	0.6
3	0.10	0.002	0.21	0.015	1.47	0.037	2.18	0.187	429	25	774	33	2.6	0.0	5.8	0.3
4	0.21	0.006	0.17	0.010	2.21	0.082	1.65	0.254	784	21	657	32	8.7	1.3	5.3	0.2
5	0.11	0.004	0.11	0.015	1.06	0.046	1.03	0.004	337	39	302	11	2.2	0.1	1.9	0.0
6	0.13	0.016	0.12	0.016	1.79	0.083	1.13	0.019	588	21	387	21	5.2	0.2	2.8	0.1
7	0.12	0.011	0.21	0.028	1.84	0.117	2.22	0.085	530	43	678	38	6.4	0.5	5.8	0.4
8	0.12	0.008	0.11	0.011	1.20	0.073	0.87	0.089	225	35	327	39	2.4	0.2	1.9	0.2
9	0.11	0.023	0.15	0.012	1.36	0.079	1.44	0.074	456	34	536	27	5.1	0.4	5.1	0.3
10	0.11	0.010	0.12	0.008	0.97	0.035	1.02	0.128	374	14	276	22	2.4	0.1	1.9	0.2
11	0.07	0.014	0.14	0.011	0.77	0.033	0.94	0.044	308	28	356	41	2.7	0.1	2.1	0.1
12	0.10	0.014	0.15	0.010	1.23	0.035	1.34	0.024	280	19	415	26	2.6	0.1	2.5	0.1
13	0.14	0.008	0.13	0.010	1.37	0.034	1.09	0.046	309	15	323	37	3.7	0.1	2.6	0.2

Table 4. Principal component analysis (PCA) based on soil management metrics for all thirteen farms. Results include eigenvalues and variable loadings for the first two principal components, which explain a total of 77.4% of the variation across all farms. The first component (PC 1) explains 55.3% of the variation, while the second component (PC 2) explains 22.1% of the variation across all farms.

PCA Loadings		
	PC1	PC2
% variation explained	55.3%	22.1%
Eigenvalue	1.82	1.15
Variable loadings		
Crop Rotation	-0.292	0.637
Tillage	-0.500	0.276
Crop Diversity	0.319	0.404
ICLS	0.421	0.113
Cover Crop	0.328	0.580
N-based Fertilizer	-0.520	0.077

FIGURES

Figure 1. Visualization of principal component analysis (PCA) results showing all thirteen farms along PC 1 (x-axis) and PC 2 (y-axis). Coefficient loadings (red arrows) are based on crop rotational complexity as an index (shown as CropRotation); frequency of tillage based on the number of passes per season (shown as Tillage); crop diversity based on the total number of crops per at the whole farm level per acres farmed (shown as CropPerArea); the use of integrated crop livestock systems (ICLS) as an index (shown as ICLS); cover crop frequency based on the average number of cover crop (CC) plantings per year, measured over a 2-year period (shown as CoverCrop); and the amount of additional organic N-based fertilizer applied in one growing season, in kg-N/acre (shown as Fertilizer). Farms are represented as points (in mustard yellow), and are numbered from 1 to 13 based on the gradient in soil management.

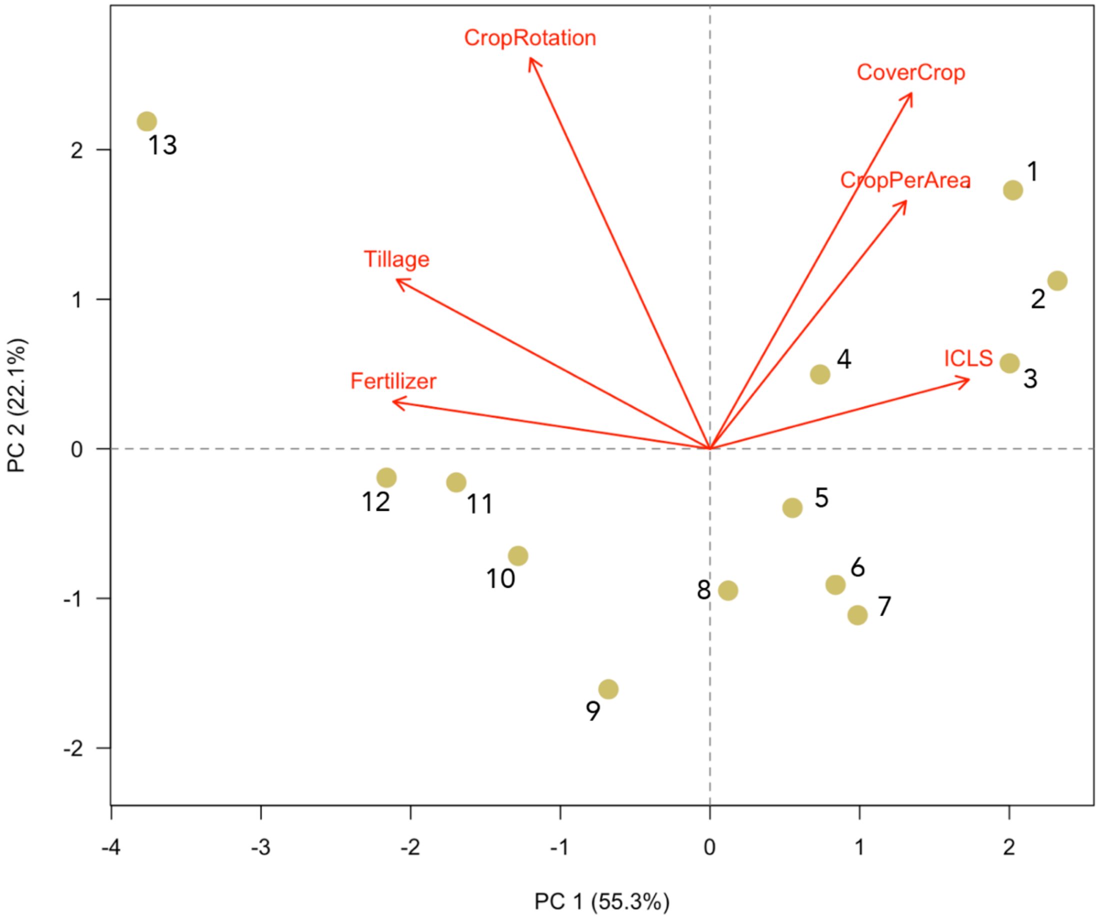
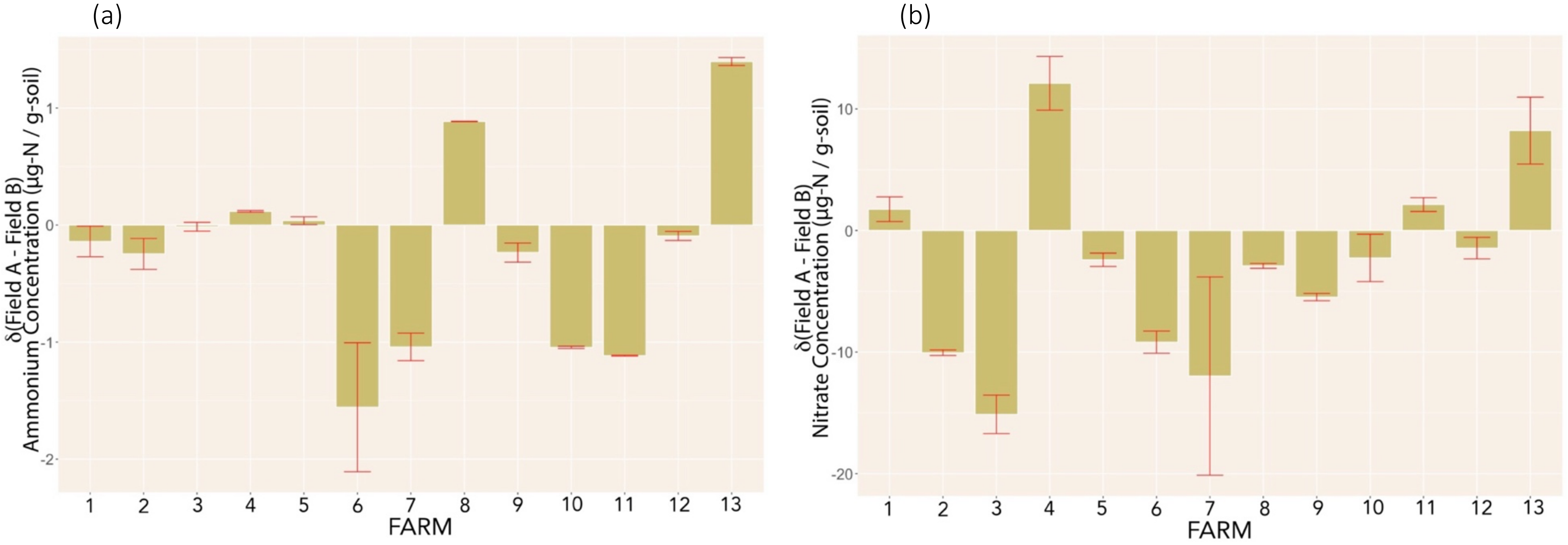
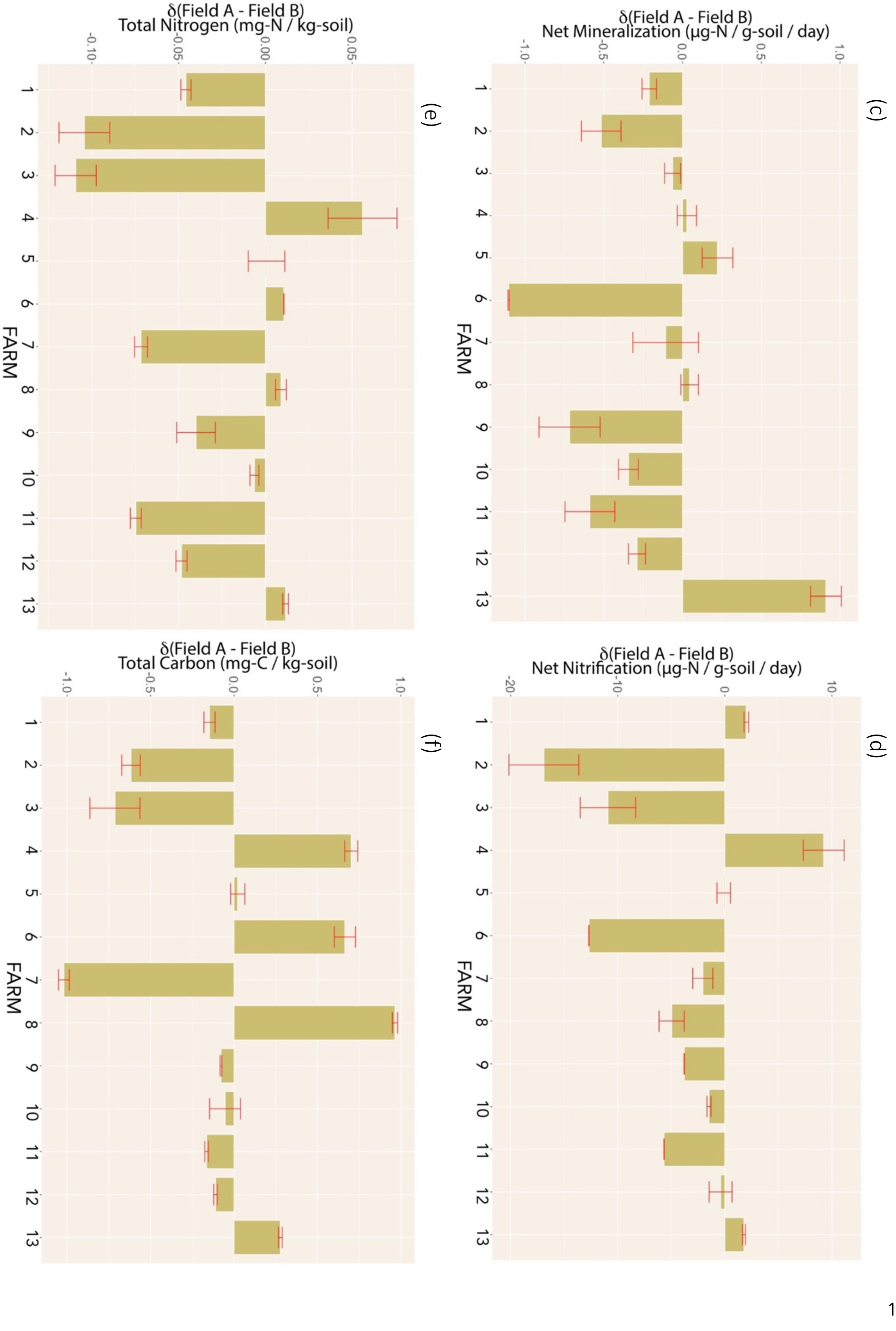
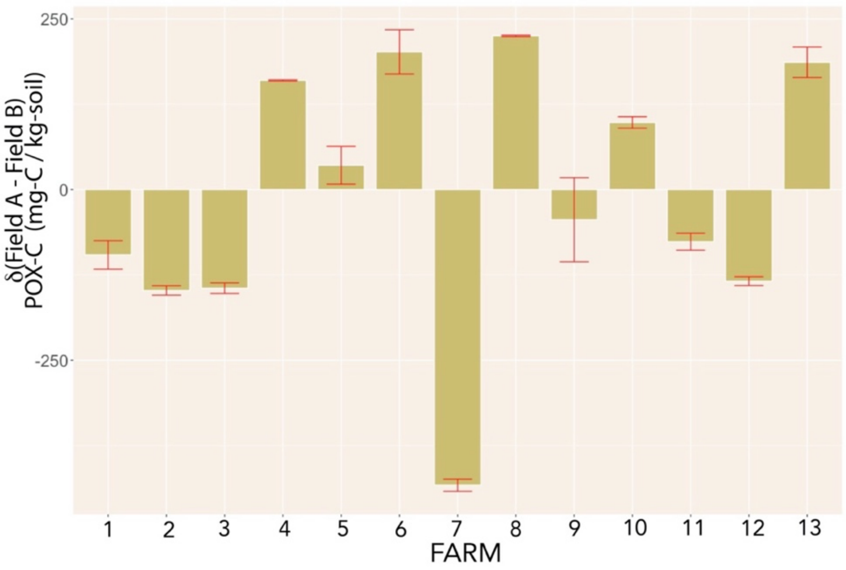


Figure 2. Bar plots comparing Field A ("least challenging" field in terms of maintaining soil fertility) and Field B ("most challenging" field in terms of maintaining soil fertility) across all farm sites for eight indicators of soil fertility, including soil ammonium (a) and soil nitrate concentrations (b), net N mineralization (c) and net N nitrification (d) rates, total soil nitrogen (e) and total organic carbon (f), POXC (g), and soil protein (h). Bars represent the difference between Field A and Field B (in mustard yellow) with standard error (in red) included; negative values show instances where Field B values were greater than Field A values. Farms are listed along a gradient of soil management (see Figure 1).


(a)
(b)

(c)
δ(Field A - Field B)
Net Mineralization (μg-N / g-soil / day)
-1.0
-0.5
0.0
0.5
1.0
FARM
1
2
3
4
5
6
7
8
9
10
11
12
13
(d)
δ(Field A - Field B)
Net Nitrification (μg-N / g-soil / day)
-20
-10
0
10
FARM
1
2
3
4
5
6
7
8
9
10
11
12
13
(e)
δ(Field A - Field B)
Total Nitrogen (mg-N / kg-soil)
-0.10
-0.05
0.00
0.05
FARM
1
2
3
4
5
6
7
8
9
10
11
12
13
(f)
δ(Field A - Field B)
Total Carbon (mg-C / kg-soil)
-1.0
-0.5
0.0
0.5
1.0
FARM
1
2
3
4
5
6
7
8
9
10
11
12
13

(g)


δ(Field A - Field B)
POX-C (mg-C / kg-soil)
250
0
-250
1
2
3
4
5
6
7
8
9
10
11
12
13
FARM

(h)

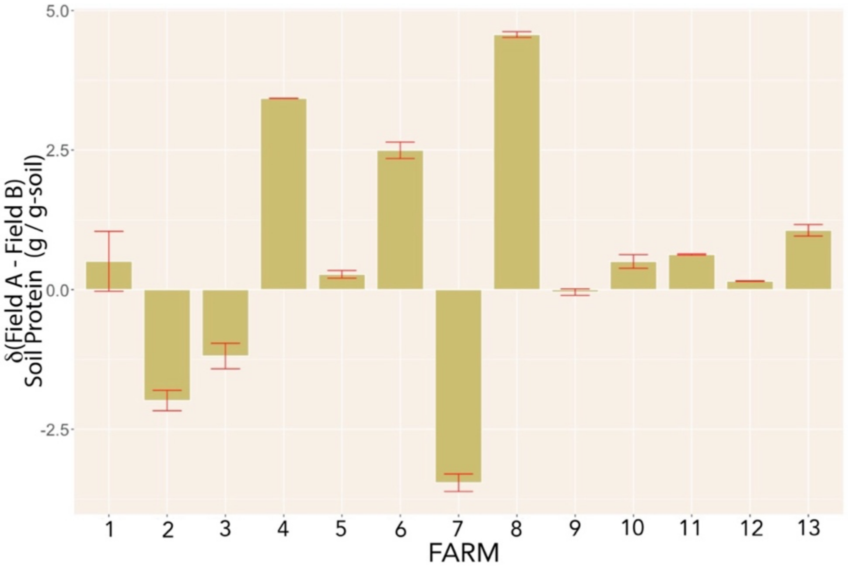
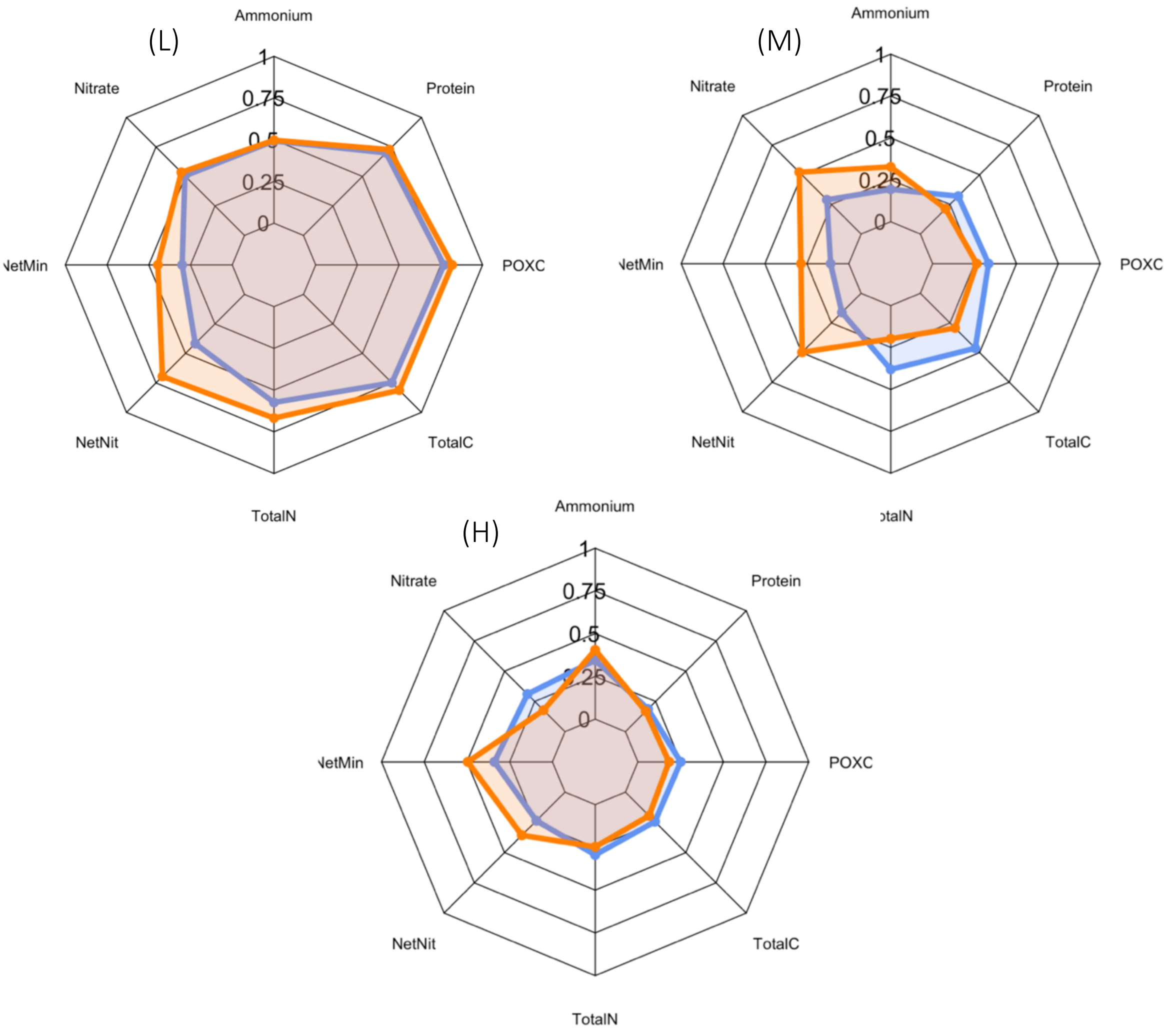

δ(Field A - Field B)
Soil Protein (g / g-soil)
5.0
2.5
0.0
-2.5
1
2
3
4
5
6
7
8
9
10
11
12
13
FARM

Figure 3. Comparison of Field A (in blue; “least challenging” field in terms of maintaining soil fertility) and Field B (in orange; “most challenging” field in terms of maintaining soil fertility) using radar plots for low N-based fertilizer input (L), medium N-based fertilizer input (M), and high N-based fertilizer input (H) farms. Low N-based fertilizer input (N=4) values ranged from 0 – 0.30 kg-N/acre; medium N-based fertilizer input (N=4) values ranged from 2 – 24 kg-N/acre; high N-based fertilizer input (N=5) values ranged from 94 – 180 kg-N/acre. Plots show all eight indicators for soil fertility, including soil ammonium and soil nitrate concentrations, net N mineralization and nitrification rates, total soil nitrogen and total organic carbon, POXC, and soil protein.



FINAL THOUGHTS

In this dissertation, I have shared a small slice of farmer knowledge of soil from a region of northern California that represents a central node of the organic movement in the United States. I have also attempted to intersect this knowledge system with agricultural researcher knowledge systems of soil. Not surprisingly, I found that the frame of reference used among farmers in this dissertation mapped out quite differently from the frame of reference used among agricultural researchers that collaborated on this work. Of course, this broader conclusion is not to say that farmer knowledge bases of soil and agricultural researcher knowledge bases of soil did not overlap at all; indeed, the two ways of knowing had much in common, as outlined in Chapter 3.

However, stepping back—as a person who was *not* born in the US and for whom English is *not* their first language—I see part of the divergence in knowledge systems among the two groups as partially stemming from a lack of a shared language (which I allude to in the final sentence of the main text of the dissertation). While I am not in any way suggesting that both knowledge bases be "watered down" to a *universal* language that strips away the richness of each knowledge base, I am suggesting that careful translation between the two knowledge bases is needed to work toward a common language.

Through my informal conversations with the local cooperative extension advisor in this region of northern California (where I centered this dissertation work), this need for a shared language among diverse agricultural stakeholders is also surfacing among her communities and networks as well. Exactly what this shift looks like in academic research practice and within the academic research process is still unfolding and in emergence as I write these words. It is clear, however, that this shift should not be delegated to science communicators and/or extension advisors as their responsibility alone; and moreover, such a shift requires fundamental change in current research frames. In this dissertation, I have provided an offering to the collective murmurations of this critical need in agricultural research that is slowly resurging.

So, in addition to widening our frame of reference as academic researchers in agriculture, there is also a need to work toward a shared language with other (currently) non-academic researchers—most imminently, farmers. Engaging in such a process can only further widen our frames as academic researchers in agriculture; ideally, the hope is that we might widen our frames and enlarge our capacity for richer language and mutual understanding so much that we are collectively rewired to allow other ways of knowing into the academic lexicon of agricultural research.

I have learned *so much* from these farmers with whom I had the honor and privilege to interact with through this dissertation work. But, if I had to elevate one nugget of wisdom that nearly every farmer always seemed to circle back towards—that was the power *of listening*, *of observing*, *of being tactile*, *of tasting*, *of smelling*, and *of being in reciprocity to* their particular milieu. Through such embedded, sensorial exchange, we can invite a multiplicity of perspectives and reanimate what is considered academic research in agriculture, and more importantly, how academic research in agriculture is carried out. In weaving together distinct perspectives and different voices, we can enlarge the whole and rewire the largely monochromatic traditions of agricultural research. In this process of rewiring, it is my modest hope that agricultural researchers can move towards creating a more textured and more complicated understanding of agricultural systems. I look forward, backward, inward, and outward to the unfurling of this hope.

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CHAPTER I – APPENDIX

SUPPLEMENT A: FARMER SEMI-STRUCTURED INTERVIEW QUESTIONS AND SURVEY.

Interview & Survey Questions
Yolo County, California

Introduction

1. How did you start farming?

2. When did you start farming? Where? Who taught you?

3. How did you *learn* to farm? What was that process like?

4. Who (or what school of thought) do you draw inspiration from for the way that you farm?

5. Why did you decide to farm? Why do you farm now? What are your goals as a farmer?

6. Who or what supports or holds you accountable for the way you farm?

7. What is your relationship to your land? (Or, what role does this land play in your life as a farmer?) Describe this relationship to your land.

Management (25 min)

1. What do you pay attention to when managing your farm in terms of caring for the land itself? Please list and describe as appropriate.

2. What management practices (in terms of caring for the land) are central to operating your farm? Why do you use those particular management practices?

3. How did you manage your farm in the beginning? When did this change? How has this changed? Have you been experimenting with any new management practices or new tools? Why did you decide to incorporate these new practices or tools?

4. Do your management practices differ from what is required of certified organic requirements? If so, in what way?

5. Why have you chosen to grow the crops (not including cover crops) that you grow? How do you choose what to grow?

6. Do you rely on seasonal or temporary workers?

Soil health (40 min)

1. What is your relationship to your soil? (Or, what role does your soil play in your overall farm operation?)

2. What types of soil do you have on your farm? Which ones are the most challenging? The least challenging? How have you learned to farm on these soils?

3. When it comes to soil management on your farm, *how* do you prioritize certain management practices over others? Specifically, how do you weigh different options (or what is prioritized) when managing for water use? For nutrients? For crop health and productivity? For weeds, pest, and/or disease? *Why* do you prioritize in this way?

4. What do you consider to be the most important management practices for maintaining your soils' health? When it comes to soil management, what is something you will never do (during bed prep or post-harvest)? What are biggest challenges related to managing your soil (climate, biophysical, ecological, economic)?

5. What do you look for when evaluating the health of your soil on your farm? On your fields, how has this indicator changed over the time you've been farming? How do you know? What do you attribute this change to? Are you satisfied with this change? Why or why not?

If doesn't come up: Does land tenure influence your decisions around farm management, particularly your soil? What are the impacts of these management practices on your profitability?

6. What nutrients do you think about when managing your soil? How do you gauge soil fertility on your farm? How do you estimate how much fertility to apply? Are there certain crops you don't fertilize?

7. Do you use your own compost? What do you look for in compost? (ie, Is it a fertility amendment or adding soil structure/OM?)

8. Do you use soil tests? If so, what types? To what extent are (commercial) soil tests useful to you? How could soil tests be more useful to you?

9. Is there anything you would like to know about your soil but don't have the capacity to observe or measure? If so, why do you want to know about this?

10. Going forward, what is important for the continued success of your farm?

11. Do you have other management practices that you wish you could implement but do not have the time or resources to do so?

12. What is the most valuable lesson you have learned from running your

13. What obstacle or situation has posed the largest challenge on your farm? How did you meet that challenge and what did you learn in overcoming the challenge?

Networks (15 min)

1. How do you learn about new practices? Who do you turn to for this information?

2. To what extent do you cooperate with other farmers? How? To what extent do you feel like you are in competition with other farmers? How? How do you hold both of those in balance?))

3. Tell me about your relationship with local extension. What sort of research would be useful to improve key shortcomings in your farming operation? Are there any issues affecting the farmers in your region currently? How are you addressing this issue?

Survey (5 min)

1. Is your farm certified organic? (Yes, No, Split) If so, since what year?
2. How many acres is your farm?
3. Of these acres, how many acres of this do you own?
4. Of the total acres, how many acres do you actively farm?
5. How many crops per season do you grow? How many growing seasons do you have per year?
6. What markets do you sell your produce to?
7. How many hours per week do you spend:

____ On your tractor / on the ground
____ In your office

____ Marketing and distribution
____ Going to meetings
____ Paperwork and compliance

8. What are your gross sales per year?
____ $0-9,999
____ $10,000-49,999
____ $50,000-249,000
____ $250,000-499,999
____ $500,000-999,999
____ $1,000,000+

9. In terms of profitability, in 2019, was your farm:
Very profitable
Profitable
Break-even
Operating at a loss
Operating at a large loss

10. How has your profitability changed over time?

1990s	____ Increased	____ Decreased	____ The same	____ Other, describe
2000s	____ Increased	____ Decreased	____ The same	____ Other, describe
2010s	____ Increased	____ Decreased	____ The same	____ Other, describe

CHAPTER II – APPENDIX

Figure S1. Soil sampling scheme used at each of 27 field sites in summer 2019. A random 10m by 20m transect area was placed on the field site across three rows of the same crop (shown in orange), away from field edges. Three composite samples based on 5 sub-samples were collected approximately 30cm from a plant at a depth of 20cm using an auger (shown in blue).

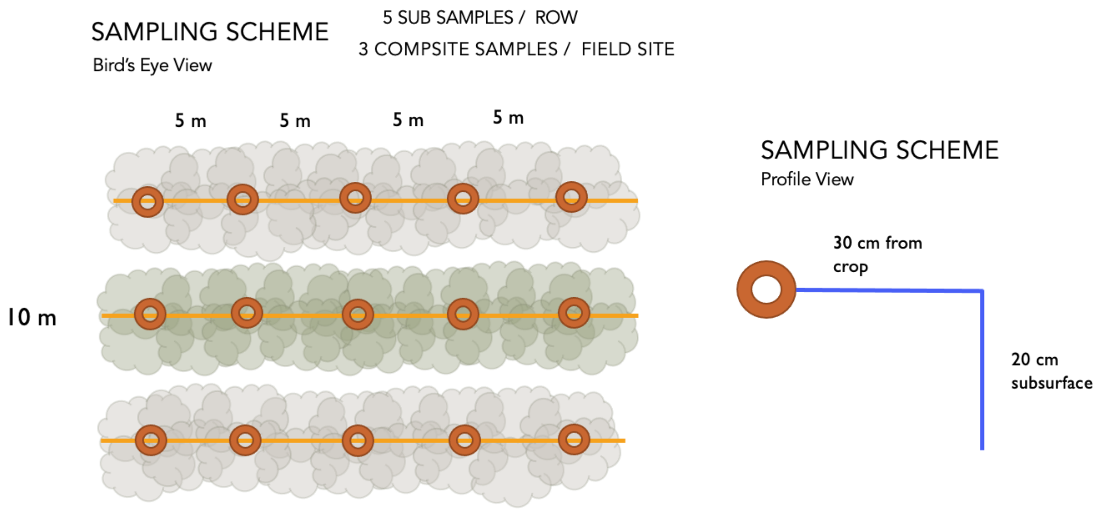


Figure S2. Histogram of differences among three clusters from the k-means clustering analysis. Each cluster represents a farm type based on indicators for soil organic matter quality. X-axis represents linear distance, and y-axis represents counts. While Farm Type I and Farm Type II do overlap between values 0 and -2, there is minimal overlap with Farm Type III.

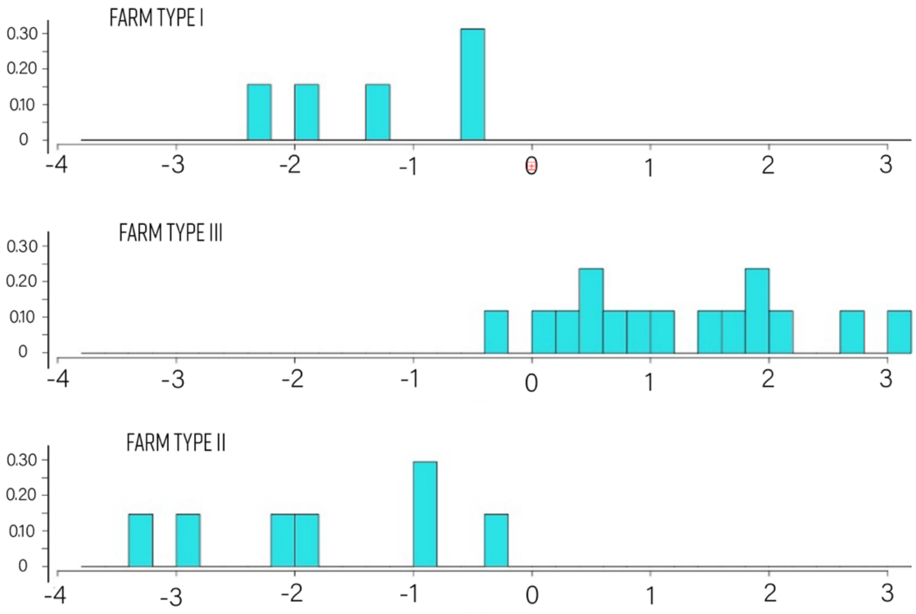
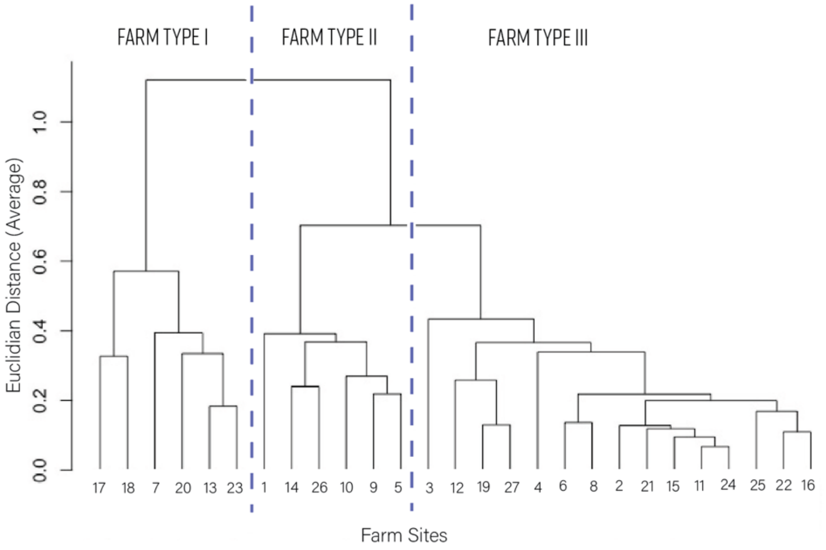
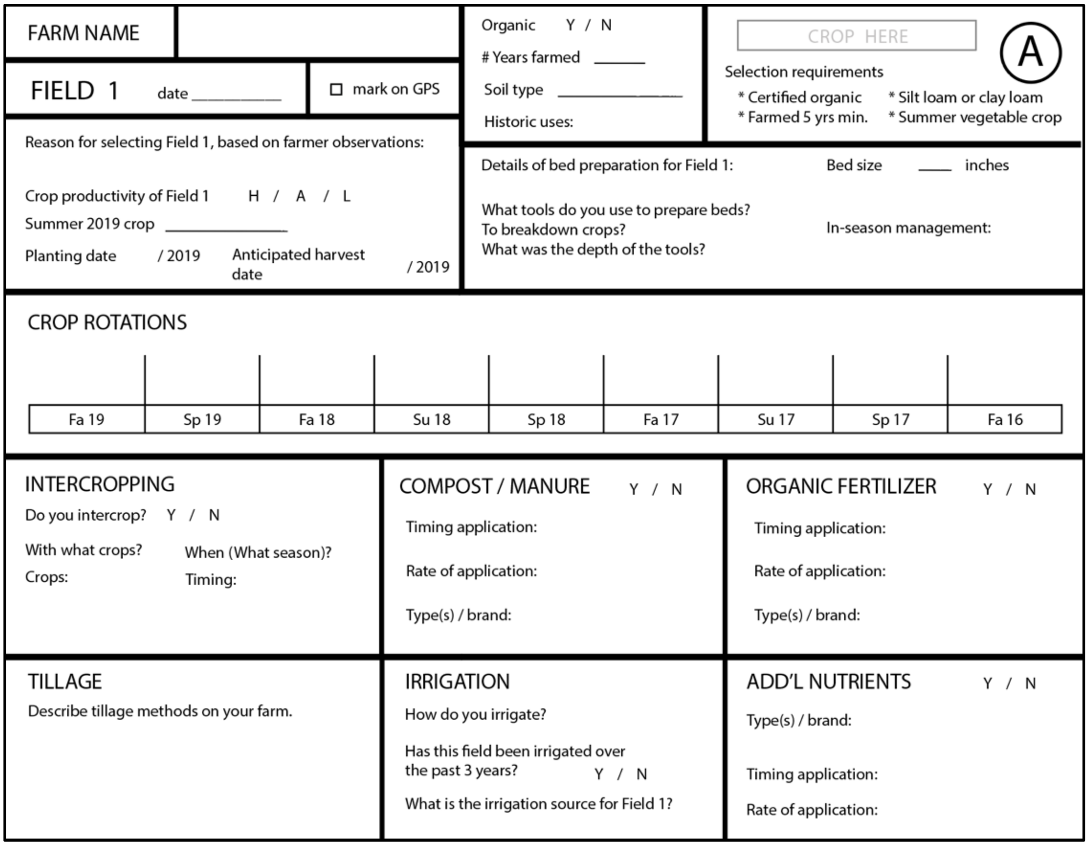


Figure S3. Dendrogram of average distance-based linkages for farm sites in Yolo County, California, created using four key indicators for soil organic matter. The dashed lines represent breaks in relatedness among farm sites, from which clusters (ie, farm types) arise.



SUPPLEMENT B: FARM MANAGEMENT SURVEY FOR EACH FIELD SITE (FIELD 1 & 2)



FARM NAME

FIELD 1 date ___________ ☐ mark on GPS

Organic Y / N
Years farmed ______
Soil type _______________
Historic uses:

CROP HERE Ⓐ
Selection requirements
* Certified organic * Silt loam or clay loam
* Farmed 5 yrs min. * Summer vegetable crop

Reason for selecting Field 1, based on farmer observations:

Crop productivity of Field 1 H / A / L
Summer 2019 crop _______________
Planting date / 2019 Anticipated harvest date / 2019

Details of bed preparation for Field 1: Bed size ____ inches

What tools do you use to prepare beds?
To breakdown crops?
What was the depth of the tools?

In-season management:

CROP ROTATIONS

Fa 19	Sp 19	Fa 18	Su 18	Sp 18	Fa 17	Su 17	Sp 17	Fa 16

INTERCROPPING
Do you intercrop? Y / N
With what crops? When (What season)?
Crops: Timing:

COMPOST / MANURE Y / N
Timing application:
Rate of application:
Type(s) / brand:

ORGANIC FERTILIZER Y / N
Timing application:
Rate of application:
Type(s) / brand:

TILLAGE
Describe tillage methods on your farm.

IRRIGATION
How do you irrigate?
Has this field been irrigated over the past 3 years? Y / N
What is the irrigation source for Field 1?

ADD'L NUTRIENTS Y / N
Type(s) / brand:
Timing application:
Rate of application:

FARM NAME

FIELD 2 date ___________

☐ mark on GPS

Organic Y / N

Years farmed ______

Soil type ______________

Historic uses:

CROP HERE

Ⓑ

Selection requirements

* Certified organic * Silt loam or clay loam
* Farmed 5 yrs min. * Summer vegetable crop

Reason for selecting Field 2, based on farmer observations:

Crop productivity of Field 2 H / A / L

Summer 2019 crop _______________

Planting date / 2019 Anticipated harvest date / 2019

Details of bed preparation for Field 2:

Bed size ____ inches

What tools do you use to prepare beds?
To breakdown crops?
What was the depth of the tools?

In-season management:

CROP ROTATIONS

Fa 19	Sp 19	Fa 18	Su 18	Sp 18	Fa 17	Su 17	Sp 17	Fa 16

INTERCROPPING

Do you intercrop? Y / N

With what crops? When (What season)?

Crops: Timing:

COMPOST / MANURE Y / N

Timing application:

Rate of application:

Type(s) / brand:

ORGANIC FERTILIZER Y / N

Timing application:

Rate of application:

Type(s) / brand:

TILLAGE

Describe tillage methods on your farm.

IRRIGATION

How do you irrigate?

Has this field been irrigated over the past 3 years? Y / N

What is the irrigation source for Field 2?

ADD’L NUTRIENTS Y / N

Type(s) / brand:

Timing application:

Rate of application: