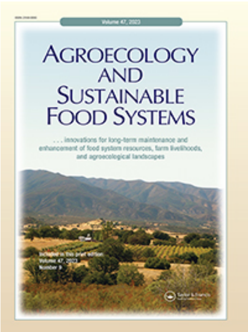

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Understanding farmer knowledge of soil and soil management: a case study of 13 organic farms in an agricultural landscape of northern California

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ABSTRACT

While it is recognized that farming alternatively is inherently knowledge intensive, in the United States, farmer knowledge has been widely overlooked and under-documented within the scientific literature. Farmer knowledge of soil in particular is understudied in the US, especially given that healthy soils have been identified as the basis for resilient agriculture. Applying an exploratory, case study approach, we interviewed 13 organic farmers based in Yolo County, California 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. We found the organic farmers in this study acquire knowledge about their farming systems primarily through direct observation, personal experience, experimentation, and inherited wisdom. To evaluate soil health, farmers in this study cited using a range of indicators, including soil structure, crop health, growth habits of weeds, and soil biology. We found that these organic farmers possess extensive place-based knowledge of their local farming systems, and that this knowledge base represents an important source for innovation and adaptive management in scientific and policy-making contexts.

KEYWORDS

Farmer knowledge; local knowledge; soil management; soil health; alternative agriculture; Farmer First

Introduction

Alternative agriculture – or agriculture that is alternative to mainstream, industrial forms of agriculture – existed prior to the 1950s as the dominant form of agriculture worldwide (Kremen, Iles, and Bacon 2012). In the United States, alternative agriculture (or farming alternatively) casts a wide umbrella

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of terms, and can include organic farming, sustainable farming, agroecological farming, diversified farming, indigenous agriculture, biodynamic farming, urban farming, conservation or regenerative agriculture, and/or permaculture – to name a few. Regardless of its form, a key feature of alternative agriculture is that it is inherently knowledge intensive (Kloppenburg 1991).

Farming alternatively requires that farmers support a knowledge infrastructure that is multi-faceted and context-specific, often informed by scientists, researchers, policymakers, government, and/or extension agents. Farmers who practice alternative agriculture amass a wealth and depth of knowledge that integrates multiple ways of knowing and that reflects diverse knowledge systems for thinking about evidence; perhaps most importantly, farming alternatively is based in practice and necessitates deep knowledge of the local (Millar and Curtis 1997; Sūmane et al. 2018). Farmer knowledge is thus an essential component of practicing alternative agriculture.

Despite the central role of farmer knowledge in alternative agriculture, this knowledge has long been overlooked in US agriculture – considered "informal" knowledge – and therefore infrequently recorded or incorporated within the scientific literature (Knapp and Fernandez-Gimenez 2009). Since the 1950s with the introduction of chemical-based, input-intensive industrial agriculture, farming in the US experienced an increase in knowledge standardization, whereby technical farming knowledge has become highly transferable, scalable, and independent of its local social or environmental context (Timmermann and Félix 2015). The simultaneous consolidation of land ownership and shift toward widespread deskilling among farmers and farmworkers in industrial agriculture have also minimized the knowledge infrastructure, while increasing the technological infrastructure, required to farm (Morgan and Murdoch 2000). As a consequence, farmer knowledge of alternative agriculture in the US has declined and has also become increasingly undervalued (Knapp and Fernandez-Gimenez 2009).

If these trends continue, farmer knowledge of alternative agriculture in the US may considerably decrease, or in some cases, become permanently lost (MacDonald 2020; Strauss et al. 2016; Sūmane 2010). Given that the role of farmer knowledge in alternative agriculture research in the US is currently overlooked, it is essential that we begin to 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 sustain this essential knowledge base in practice; it is equally critical to document the particularities of farmer knowledge in local contexts. Farmer knowledge may provide an essential knowledge base that can inform and extend scientific research in alternative agriculture, and also potentially inform and extend the knowledge base of contemporaneous and future generations of farmers, policymakers, and agricultural industry experts.

Moving forward, there is a need to elevate the importance and legitimacy of farmer knowledge across disciplines within agriculture such that farmer knowledge is considered a valued knowledge base within alternative agriculture research, policy, and beyond (Flora 1992; Strauss et al. 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 (Adamsone-Fiskovica and Grivins 2021; Morgan and Murdoch 2000; Oudwater and Martin 2003; Stoate et al. 2019), in this paper we maintain that farmer knowledge represents a systematic way of knowing, and therefore warrants formal, standalone documentation and incorporation within the scientific literature (Collins and Evans 2002; Oliver et al. 2012; Thrupp 1989).

Farmer knowledge in context

Farmer knowledge is a type of local knowledge (Antweiler 2019). As such, farmer knowledge, especially in the context of alternative agriculture, becomes relevant when linked to a particular local context (Thrupp 1989). 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 (Agrawal 1994; Antweiler 1998; Nygren 1999), which means that local knowledge is place-based and dynamic. Though other types of local knowledge, such as "traditional," "folk," or "indigenous" knowledge, may take generations to develop, Maltz (2013) contends that certain types of local knowledge – like farmer knowledge – may develop even within one or two generations of place-based experience. This suggests that research on local farmer knowledge of alternative agriculture may be possible even in places where a long tradition of agriculture is lacking.

In this sense, soil and on-farm management of soil presents a unique entry point for studying farmer knowledge in alternative agriculture, particularly in the US – because regardless of the length of a farmer's tenure, developing local knowledge of soil is foundational to farming alternatively. Local knowledge of soil enables knowledge holders to farm productively and understand the local ecological systems upon which their farm operation depends (Oudwater and Martin 2003). It is widely known that healthy soils are the basis for agriculture (Lehmann et al. 2020; Wander et al. 2019). At the same time, soil is heterogeneous across landscapes (Li et al. 2021). For example, even at the scale of a single field, differences in soil microenvironments, management histories, inherent soil characteristics, and time of year can 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 practicing alternative agriculture – where place-based knowledge of soil is an important aspect of building and sustaining healthy soils on-farm – and more broadly, resilient agriculture (Barrera-Bassols and Zinck 2003; Davis, Huggins, and Reganold 2023; Peterson, Eviner, and Gaudin 2018).

In the U.S., 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 farmer knowledge in the context of alternative agriculture. 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, Erickson, and Young 2010). Even fewer studies currently exist at the intersection of farmer knowledge, alternative agriculture, and soil management. Though there is documentation of farmer knowledge of soil management in sustainable agriculture, most studies focus within the "development" context outside of US alternative agriculture (Beckford and Barker 2007; Kpienbaareh et al. 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 (Anderson 2013; Martin et al. 2010), and lacks focus on production agriculture.

To consider this gap, we focus this exploratory study on a significant epicenter for alternative agriculture in the United States: present day Yolo County, California, also referred to as the unceded tribal lands of the Cachil Dehe Band of Wintun Indians of the Colusa Indian Community, the Kletsel Dehe Wintun Nation, and the Yocha Dehe Wintun Nation. This agricultural 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 farming alternatively – specifically, the organic movement – and where a large concentration of diversified fruit and vegetable 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 coastal Santa Cruz – 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 to 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.

Yolo County became one of a few 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 U.S.) 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 of experience) – 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).

Informed by the organic movement, these so-called "back-to-the-land" farmers established innovative, high-value, diversified farms that still exist today. As diversified fruit and vegetable farmers, their approach to farming necessitated learning about and working with their local landscape and ecology (Kremen, Iles, and Bacon 2012). Upon arrival, many were particularly interested in soil fertility and made 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 2000). 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 (Lincoln and Ardoin 2016; Sūmane et al. 2015).

To our knowledge, 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 particular farmers have translated their local knowledge of soil into practice and the substance of the soil management practices applied. To address this gap, we used an exploratory approach and examined local farmer knowledge of soil 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.

Materials and 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 and Ghildyal 1985; Chambers, Pacey, and Thrupp 1989). 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 (Drinkwater, Friedman, and Buck 2016; Scoones and Thompson 1994). We used an open-ended, qualitative approach that relies 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; Sayre 2004); 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 farmers 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

This research was part of a larger project examining soil health on working organic farms in the region. 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 (ie, *not* monocrops); located in (or within 10 miles of) Yolo County; at least 10 years of experience in organic farming; and, at least five years of farming on the same land. We chose to focus on diversified fruit and vegetable farmers specifically because of the high demands on soil health and management necessary to farm fruits and vegetables alternatively (Walthall et al. 2013). We placed minimum limits on farmer experience and time on a particular piece of land in order to ensure farmer knowledge had time to develop; based on an informal survey of farmers throughout California, 10 years was the consensus among these farmers as the amount of time needed to experience aspects of farming "at least once." 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 -11,014).

Working with a local UCCE advisor helped establish trust with farmers identified. These 16 farmers were contacted with a letter containing information about the study and its scope. Thirteen 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 13 organic farmers represent a majority (>80%) of the organic farms in the region that grow a diversified array of vegetable and fruit crops and that sell to a variety of consumer markets, including farmers' markets, wholesale markets, and restaurants. These farmers interviewed also represented 13 individuals who oversaw 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.

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 13 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 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 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 descriptive 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. First, we tallied both the number of coded passages regarding different themes or topics, and the number of farmers who addressed each theme. Second, 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 a small window into 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. Where we reference "the farmers" in the sections below, they refer specifically to the farmers in this study, not all farmers.

Below, we introduce farmer demographics of this study, situate these farmers' knowledge in terms of their connection to the land, and also provide insight on how farmers in this study accumulate knowledge; finally, we synthesize key themes that emerged from farmer interviews with regards to soil health and soil management.

Farmer demographics

We interviewed 13 organic farmers, which represents about 80% of certified organic vegetable growers in Yolo County, California who focus on growing diversified crops and have been farming for at least 10 years. Farmer participants were majority ($N = 12$) white and all either first or second generation settlers in Yolo County, CA. This interview pool included 10 men and 3 women between the ages of 45 to 70. 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 of the 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 ($N = 3$) were second generation farmers, and the remainder ($N = 10$) were first generation farmers. All the farmers had been farming for at least a decade, and most of the 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. For example, these farmers had either moved across the country to an unfamiliar place, had quit their office job, and/or had lost an important family member or their childhood home.

Connection to the land

Farmers interviewed 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 (i.e., Yolo County), the farmers described their relationship to the land they farmed. Not surprisingly, many of the farmers initially responded with personifications of their land (e.g., "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 (e.g., "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 (e.g., "I love where we are;" "I love my land;" "The land is very much a gift."). Several of the farmers ($N = 5$) characterized their role as a responsibility (e.g., "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 interviewed 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. The 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 the farmers also explicitly commented on the fact that they have never stopped learning to farm (e.g., "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 in this study 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. Experimentation consisted of methodical trials that farmers implemented at small scales on their farms, and 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 or to increase alignment with their own values, or a need to pivot in order to adapt to external changes. The 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 her 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, Eviner, and Gaudin 2018). For this farmer, this small experiment was monumental and shifted her entire farm toward a management system that was more in alignment with her personal farming values. 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 for this particular farmer 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 (e.g., "I walk around every place and I look at it, that is my daily walk."). Several of the farmers summed up their cycle of learning as a cycle of observation, trial, feedback, observation, trial, feedback, etc (e.g., "Do things, they don't work, so I talk to people, copy people, try your own ideas;" or "You make mistakes and you learn by those. I think it's a lot of observation.").

The farmers frequently mentioned fellow farmers as a source of learning as well. However, several of the 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 [he] 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 of the 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 the farmers, older mentors were identified as key in their development as a farmer. Nearly all the farmers ($N = 11$) interviewed mentioned an important older mentor early in their career that helped them to learn the foundations of farming. A few of the 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*." About half of farmers expressed concern about finding a new generation of farmers to take over their operation and worried about what would happen if they didn't (e.g., "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

Interfacing with soil

The farmers discussed how they view their soils as part of their larger management system. Nearly half ($N = 6$) 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, on particular fields, and also allowed them to compare soils across their farm and across different fields. Three of these farmers stated explicitly that they viewed their soil as alive and/or a living organism.

A few of the farmers ($N = 3$) did not directly 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 farms.)

Evaluating soil health

During the initial field visit, the farmers shared their definitions of soil health. Across all farmers interviewed ($N = 13$), responses appeared mechanical and resembled language disseminated by government entities such as the Natural Resources Conservation Service (USDA-NRCS 2012). As such, most responses emphasized building soil organic matter, promoting biological (e.g., 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, the 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, the 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 gray 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, the farmers tended to first grow cover crops to establish a baseline for soil health and also understand soil behavior and/or soil type. The farmers also 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, the 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 of the 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." Soil structure and soil crumble were also flagged as good physical indicators of soil health by more than half of the farmers ($N = 7$). Farmers interviewed determined soil structure in a variety of ways, which 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 the farmers ($N = 10$) explicitly stated that they did not rely on soil tests to provide information regarding the health or status of their soils; only a handful ($N = 3$) of the farmers communicated that they actively used soil tests. The farmers who did not use soil tests noted that commercially available soil tests were often inaccurate, not calibrated to their scale and/or type of operation, lacked enough data points to be useful, and/or did not provide any additional information that they were not able to already readily observe day-to-day or long-term on the farm.

Farmer knowledge of soil management

Managing soil for fields or for crops

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 (ie, 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 correspond with farm size, farmer values, or soil type.

Prioritizing timing and appropriate windows

Several ($N = 4$) of the 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

The following two key practices emerged as the most central to building healthy soils on farm for farmers interviewed. Farmers expressed that maintaining soil structure was the foundation for sustaining soil health and good soil management. Farmers also indicated that minimizing external inputs (eg, fertilizers) to create a closed loop system was at the heart of their soil management values.

Maintaining soil structure

All the farmers ($N = 13$) centered discussion of key soil management practices on the importance of maintaining soil structure. While some ($N = 6$) discussed this key management practice in terms of working ground during appropriate windows of soil moisture, others ($N = 7$) 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 this 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 interviewed 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 therefore healthy, productive soils. The 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 of the 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 of the 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 harrows], 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 of the 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. 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 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, the 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.

Minimizing external inputs

Most of the 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, the 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 of the 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 the 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, the farmers have had to pivot to different solutions. For a large portion of 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 ($N = 5$) 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 soil and farming systems. Results show that white, first- and second-generation farmers that farm alternatively 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 (e.g., Western science) that inform farming systems.

While the content and application of farmer knowledge may be locally specific (as emphasized previously), below we consider aspects of this case study that may be more broadly applicable. First, we discuss emergent mechanisms for farmer knowledge formation using existing frameworks in the social-ecological systems (SES) literature, and also summarize key features of farmer knowledge that coalesced from the results of this study.

Mechanisms for farmer knowledge formation

To further examine how farmers in this study acquire and incorporate their knowledge within their farm operation, we first explore emergent mechanisms that underpin farmer knowledge formation.

Because farmer knowledge encompasses knowledge of both social and ecological systems – and the interactions thereof – it is useful to draw upon existing frameworks from the social-ecological systems (SES) literature in order to trace the process of farmer knowledge formation among farmers in our case study. Briefly, social-ecological systems recognize the importance of linking social and ecological processes to capture interactions between humans and the environment; importantly, existing literature within SES studies also emphasizes the interactive and adaptive feedback among social and ecological processes that link social and ecological system dynamics (Berkes, Folke, and Colding 2000; Schluter et al. 2019).

Boons (2013) offers a conceptual guide for identifying social-ecological mechanisms, which adapted to our case study provides a starting point for tracing aspects of farmer knowledge formation. Here, social-ecological mechanisms for farmer knowledge formation refer to – on the one hand, social and cultural phenomena that influence farmer knowledge and their personal values – on the other, farmers' observations of and experiences with environmental conditions and ecological processes on their farms that influence their knowledge and their values – and the interactions thereof (Berkes, Folke, and Colding 2000; Boons 2013). Drawing upon Bar-Tal (2000), we further define farmer values 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, production ethos, etc).

In our study, examples of social-ecological mechanisms for farmer knowledge formation among these farmers included direct observation, personal experience, on-farm experimentation, and inherited wisdom from other local farmers. Similar to Boons' (2013) conceptual guide, our results suggest that social-ecological mechanisms may play a central role in producing a farmer's values and in integrating ecological knowledge into their farm operation. At the same time, results also highlight that social-ecological mechanisms may contribute to a farmer's local ecological knowledge base, and importantly, place limits on the incorporation of social values in practice on farms. It is possible that social-ecological mechanisms may also provide the lens through which farmer values and ecological knowledge are reevaluated over time. Moreover, farmer values may also mutually inform ecological knowledge – and vice versa – in a dynamic, dialectical process as individual farmers apply their values or ecological knowledge in practice on their farm.

Social-ecological mechanisms may also be key in translating abstract information into concrete knowledge among farmers interviewed. For example, experimentation may codify direct observations to generate farmer knowledge that is both concrete and transferable; or, to a lesser degree, personal experience may enhance farmer knowledge and may guide the process of experimentation. In general, we found that 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). This finding underscores that for these farmers, their theory of farming is embedded in their practice of farming, and that these farmers tend to derive theoretical claims from their land.

For example, the farmers who possessed a stewardship ethos viewed themselves as caretakers of their land; one farmer described his 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 acquired ecological knowledge in turn directly informed how farmers approached management of their farms and the types of management practices and regimes they applied. That said, farmer values from this study did not always 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, the heavy clay present in his soil, and the need to have crops ready for early summer markets.

In another example, several of the 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 (e.g., 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 codified in mainstream farming guidebooks, policy recommendations, or the scientific literature (Dunn et al. 2016). 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 of the farmers considered this process "trial and error," in actuality, all farmers in this study 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 (Berkes, Colding, and Folke 2000; Holling 1978). This critical link between farmer knowledge formation and adaptive mangement is important to consider in the broader context of resilience thinking, wherein adaptive management is a tool in the face of shifting climate and changing landscape regimes (Folke et al. 2010; Holling 1973). The underlying social and ecological mechanisms for farmer knowledge formation discussed here may have a role in informing adaptive management and pathways toward more resilient agriculture (Allen et al. 2011; Carlisle 2014). In this sense, farmer knowledge represents an overlooked source for informing innovation in farming alternatively. Farmer knowledge provides an *extension* to scientific and policy knowledge bases, in that farmers develop new dimensions of knowledge and alternative ways of thinking about aspects of farming 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 agriculture that is resilient to increased planetary uncertainties (Folke et al. 2010; Stankey et al. 2005).

Synthesis of key aspects of farmer knowledge

Mapping mechanisms for how farmers learn and codify local knowledge provides necessary groundwork to connect farmer knowledge formation to farm management in practice. Below, we synthesize key insights about farmers from this study. While these insights may or may not be generalizable, they provide a starting point for engaging with farmers in alternative agriculture in future studies.

Farmer knowledge is informed by experiential learning

Farmer knowledge accumulation by farmers in this study was mostly observational and experiential. Most of the 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 embedding theory in 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 in alternative agriculture thus may provide an important node in the research and policymaking process, whereby they assess if scientific findings or policy recommendations may or may not apply to their specific farming context – through direct observation, personal experience, and experimentation.

Farmers engage in systematic knowledge making

Similar to Sūmane et al. (2018), we found that the process for farmer knowledge formation, or precisely how farmers learn, is systematic and iterative in approach. In this study, farmer ecological knowledge was developed over time based on continuous systematic observation, personal experiences, and/or experimentation. This systematic approach that relies on iterative feedback to learning applied among these organic farmers is akin in approach to examples of adaptive management in agriculture (Rist et al. 2013).

As highlighted in the results, it is possible for a farmer to acquire expert knowledge even as a first- or second-generation farmer. Documenting this farmer knowledge within the scientific literature – specifically farmer knowledge in the context of relatively new (eg, first- or second- generation) alternative farmers in the US – represents a key way forward for widening agricultural knowledge both in theory and in practice (Carlisle et al. 2019). This study provides one example for documenting this farmer knowledge in a particularly unique site for alternative agriculture. Future studies may expand on this approach in order to document other sites with recent but practical agricultural knowledge on alternative farms.

Farmer management is holistic

Farmers in this study tended to think holistically about their farm management. For example, when the farmers were asked to talk about soil management specifically, several of the 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 10 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 in this study, maintaining ideal soil structure was the foundation for healthy soil. The farmers emphasized that ideal soil structure was delicately maintained by only working ground at appropriate windows of soil moistures. Determining this window of ideal soil moisture represented a learned skill that each individual farmer developed through an iterative learning process. 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 these farmers developed their ecological knowledge of the appropriate windows of soil moisture, their values around soil management often shifted. In this way, over time (and with a steep learning curve), farmers in this study 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 lasting consequences and often took years, in some cases even a decade, to rebuild.

This key soil health practice voiced by a majority of farmers interviewed was distinct from messaging about soil health vis-a-vis extension institutions (such as the USDA-NRCS (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 (USDA-NRCS 2012). 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.

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 geographical 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 some 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 farms that practice alternative agriculture to be able to adapt to everchanging social and ecological changes ahead (Darnhofer et al. 2010; Sundkvist, Milestad, and Jansson 2005). 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* (ie, three or more) 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 family or individual 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, safeguard farmer knowledge, and promote adaptations in alternative agriculture into the future. As Calo (2018) and others point out, technical knowledge dissemination alone will not resolve this ongoing challenge of farm succession, as larger structural barriers are also at play – most notably, related to land access, transfer, and tenure (Carolan 2018; Valliant et al. 2019).

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 (farmer knowledge formation; working with local extension agents; interview questions applied – see Supplement A) particularly to similar farming systems, the farmer knowledge presented in this study may or may not be generalizable or 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 required considerable time and effort. While surveys often provide a way to overcome time and budget constraints to learn about farmer knowledge, this study suggests 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 or 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 neglected or overlooked by the scientific community, policymakers, and agricultural industry experts; however, this study makes the case for inclusion of farmer knowledge in these arenas. In-depth interviews showed that farmers may provide an important role in translating theoretical aspects of agricultural knowledge into practice. It is for this reason that farmer knowledge can be better understood in the context of working farms and the local landscapes they inhabit.

As one of the handful of systematic assessments of local 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 local advisors in combination with community referrals provides 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 that can extend scientific research in alternative agriculture. This study provides an exploratory, local 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 and adoption of alternative agriculture can widen its frame to encompass a more varied understanding of farming systems and management motivations.

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