ASSESSMENT OF NITROGEN FLOWS ON DIVERSIFIED ORGANIC FARMS: A ROAD TOWARD ENHANCING SOIL HEALTH FROM THE GROUND UP

FINAL REPORT

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1. SUMMARY

Soil health is ideally a central part of organic farm management. One key question is how *diversification practices* (e.g., diversified crop rotations, cover crops, etc) on organic farms build soil health and in turn influence how and when nitrogen is made available from soil organic matter. This question is particularly important to consider when determining the timing and choice of organic fertilizer application across organic farms that engage varying levels of diversification practices. While nitrogen mineralization (i.e. the process by which nitrogen transforms from organic nitrogen to inorganic nitrogen and available for plant uptake, has been widely studied) we explored a novel approach to understand nitrogen flows on working organic farms. Whereas previous studies focused on measuring pools of nitrogen and/or relying on proximate indicators of nitrogen cycling (e.g. soil proteins), we are quantifying **nitrogen fluxes** (i.e., gross nitrogen mineralization and nitrification) on working organic farms.

To do so, we incorporated experiential knowledge of organic farmers on soil health and fertility, in combination with technical, *in situ* measurements of nitrogen flows in their soil. Based on initial farm visits and in-depth 2-hour interviews, we developed a system to rank on-farm diversification for the 13 organic farms studied and sampled. The preliminary results of this project reinforced the initial hypothesis that some organic farms in Yolo County exhibit relatively low inorganic nitrogen levels, illustrating how organic farmers must be cautious about how to interpret assessments of nitrogen availability from commercial soil tests. As mentioned in the proposal, these data will complement the gross N mineralization and nitrification data once completed and provide information on actual soil nitrogen cycling across different systems of farm diversification.

2. INTRODUCTION

Organic production that emphasizes diversified farming practices represents a key pathway towards sustainable agriculture (Iles & Marsh, 2012; IPES, 2018). Diversified farming systems (DFS) are defined as agricultural systems that intentionally promote *functional* diversity at multiple spatial, temporal, and ecological scales through diversification practices, that in turn enhance ecosystem functions across these scales (Kremen and Miles 2012b). Ideally, organic agriculture embodies this focus on functional biodiversity in order to manage and renew soil fertility using internally-regulated biological soil processes (e.g., implementing diversification practices) that minimize reliance on external inputs like organic fertilizers. In reality, however, many certified organic farms vary in the extent to which they depend on managing for functional biodiversity rather than relying on external organic inputs.

One likely reason for this disconnect in management approach is that efficient fertility management remains a key challenge for organic farmers. Determining how much organic fertilizer to apply and when to apply is a tricky process—as too much fertilizer is a potential waste of money and may pollute air and water due to excess loss of nutrients, while too little fertilizer can lower crop yields. In the case of high-value vegetable systems, as found in California, a significant number of organic farmers are dependent on highly labile organic fertilizers such as seabird guano and fish emulsion that can increase risks of nitrogen losses (Bowles et al. 2015). These organic fertilizers are also expensive, and represent a significant added cost to production for these farmers.

Based on initial conversations with organic farmers in Yolo County, several farmers had expressed interest in curtailing application of these organic fertilizers to reduce costs and limit environmental impacts. Many of these of farmers had already implemented a wide range of diversification practices, including diversified crop rotations, cover cropping, intercropping, residue management, and compost application, that build soil organic matter (SOM) and can improve plant available nitrogen (N); however, these farmers did not have adequate information on when and how much N is actually available to crops—particularly as diversification practices increased their soil health increased over time.

While commercial soil health tests provide information on N availability on farms, such tests possess a wide range of shortcomings, including accurate estimation of flows of N in soil. For example, crop fertilizer recommendations often cite standard values for N mineralization. These recommendations do not account for on-farm diversification practices and/or historically amended soils that build SOM and that may alter the N mineralization rates in soil differently across individual farms. Accurately quantifying N mineralization rates is essential; however, the rate of N made available to crops from SOM or cover crop residues (i.e., N mineralization) can increase substantially in systems that emphasize building healthy soils with high levels of organic matter and active soil microbes (Burger & Jackson 2003).

Most indicators of plant available N currently available in commercial soil tests provide static information on soil N that are either slow-changing (eg, total N, % soil organic matter) or partial and possibly misleading indicators (e.g., soil nitrate). One reason common measurements of inorganic N pools can be misleading is because such measurements do not encompass the dynamic flows of N in soils, which constitute the true N mineralization and nitrification capacity of the soil. Yet, efficient fertilization requires assessing for the N mineralization potential of soil rather than pools of N in soil. This ongoing gap in available soil tests continues to be a key barrier among diversified organic farmers who have been building their soil health for decades but have no direct way to measure rates of N mineralization. Our research was motivated by this gap in available soil tests to organic farmers. **A central driver to our research work was to identify how particular diversification practices impact the plant-soil-microbe interactions that underpin N availability and the potential for N loss—in order to fine-tine our understanding of how both crop productivity and minimal N losses to environment can be achieved.**

To better understand and assess flows of N in soil, our project diverged from traditional and commercial approaches to assess plant N availability on organic farms. Rather than focus on *pools* of inorganic N, in particular nitrate (NO_3^-), as indicators of N availability, which can be misleading, our research focused on quantifying N *flows* on working organic farms in Yolo County. At the outset of this project, the efficacy of non-commercially available soil tests to predict N cycling had not been widely tested in field conditions on working organic farms. In addition, to our knowledge, no prior research had quantified actual N flows on working organic farms, particularly across varying levels of diversification practices agriculture (Drinkwater & Snapp 2007). One reason for this is that soil properties like N mineralization rates across a single farm can be highly variable, emphasizing the need for site-specific information (Masunga et al. 2016). It is for this reason we chose to center our research on working farms, across a gradient of diversification practices.

Beyond understanding N flows on working farms, our research was also strongly motivated by organic farmers' needs. We recognized from the outset that without widespread buy-in from organic farmers, this research lacked relevance beyond the scope of the farmers in this study. To address this, we drew upon a growing body of work that has demonstrated the importance of farmer-to-farmer knowledge sharing in the uptake of new tools and innovative practices that enhance on-farm soil health (Dolinska & d'Aquino, 2016). Prior research on organic farms suggested that regional, farmer-to-farmer networks and learning days can be highly effective in sharing and diffusion of new tools and diversification practices that improve soil fertility and reduce the need for external organic inputs (Goulet 2013). When combined with *in situ* measurement of soil N mineralization rates, such an approach provided organic diversified farmers with access to more precise and reliable information for improved fertility management—based on the innovations of individual farmers. Both the outreach and research components of this project supported the emergence of farmer-to-farmer networks within the region of our study. The approach was motived by a key opportunity to facilitate knowledge sharing of practical approaches in order to improve soil health and fertility, and optimize the use of organic fertilizers on individual farms.

3. OBJECTIVES

The overarching goal of this project seeks to understand how diversification practices that build soil health influence how and when nitrogen is made available from soil organic matter. Specifically, we wanted to link how diversification practices and organic fertilizers interact to influence soil nitrogen flows and nitrogen availability across diversified organic farms in the Yolo County region. Our objectives were to:

1) Investigate the extent to which and why organic farmers in Yolo County rely on external organic inputs;
2) Understand flows of N in soil (ie, gross mineralization and nitrification rates) relative to commercial indicators of available N on working organic farms with varying levels of diversification; and,

3) Facilitate farmer-to-farmer knowledge sharing of diversification practices that boost on-farm soil health and improve fertility management—in particular how healthy soils impact N cycling and how farmers can better assess N availability.

While our objectives for the project did not change, the extent to which we were able to achieve these objectives under our original timeline were significantly limited by the pandemic that began in early 2020. To date, we have been able to work through much of Objective 1 and Objective 3; however, we continue to work on Objective 2 at the limited capacity allowed for by restrictions due to the pandemic.

4. METHODS

Site description

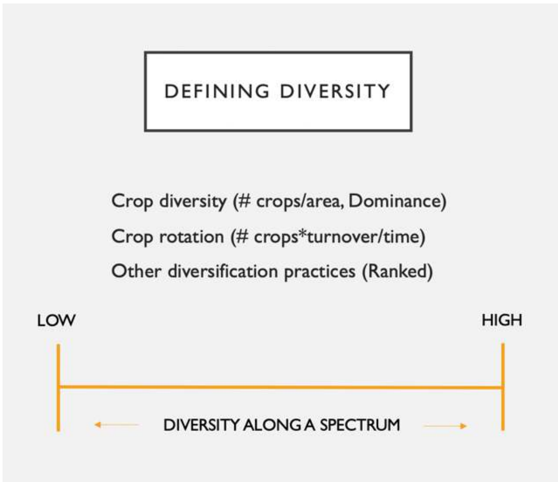
We conducted this research project in collaboration with 13 certified organic farms in Yolo County, California. For context, this region is home to a high number of innovative organic farmers that have made soil health a priority for decades, and therefore presents a unique opportunity to measure the cumulative effects of long-term management for healthy soil. Yolo County is also an area with a large number of high-value vegetable systems, where economic considerations and associated risks represent a large factor in decision-making around nutrient management and fertilizer application.

Interviews

We recruited and interviewed 13 organic farmers across a range of diversification, from low diversification to highly diversified. This metric was based on varying levels of diversification practices employed (i.e., diversified crop rotations, cover crops, total crop diversity, etc). The 2-hour semi-structured interviews were conducted orally and in person (with the exception of 3 farmers, post-pandemic). From the interviews, we determined: (1) the varying levels of diversified farming practices employed, (2) the indicators of soil fertility each farmer currently uses, and (3) how these indicators affect management decisions (crop rotation sequence, cover cropping, compost application, etc) and the choice, timing, and amount of organic fertilizers used. To date, we have interviewed and transcribed 10 out of the 13 farmers, due to COVID-related delays.

Site selection

Based on a separate initial farm visit, we co-selected 2 soil sampling sites per farm *with farmers* to incorporate farmer knowledge of relative soil health. We asked farmers to show a field where they feel they had made the most investments in promoting soil fertility (Site A) and a field with the least investment (Site B), and discuss differences between the two fields in terms of soil health. We used these sites to sample soils across 26 farm sites (2 sites per farm, 13 organic farms total) and 2 additional control sites (at the Russell Ranch Sustainable Agriculture Facility in Davis, CA, a long-term experiment comparing several types of farming systems, including organic). We selected sites with similar soil types based on SSURGO maps and farmers' descriptions and collected 3 subsamples per site (which consisted of three row transects with five composite samples per transect). We sampled soils around peak crop



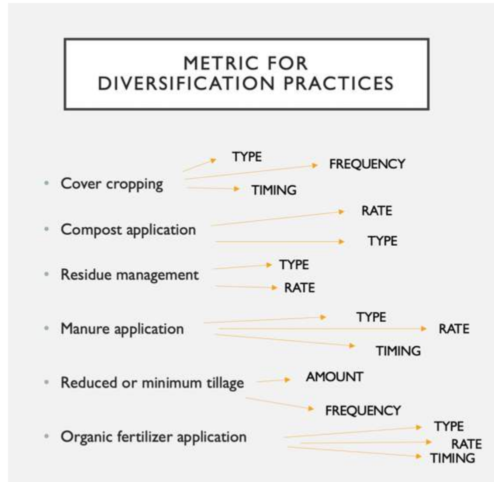


Figure 1 (a) To categorize organic farms across a spectrum of diversity from low to high, we used three key parameters: crop diversity, crop rotation, and ranked diversification practices. Figure 1 (b) on the right further details the specific metrics for diversification used to rank each organic farm across the spectrum.

vegetative growth, when crop N demand was highest. We did not control for specific crop type across sites, because we aimed to measure long-term, cumulative effects of soil health independent of crop type; however, to control across fields, we sampled only in fields with all summer vegetable crops. Within fields, we sampled the bulk soil, approximately 30 cm from the plant, at 15 cm depth.

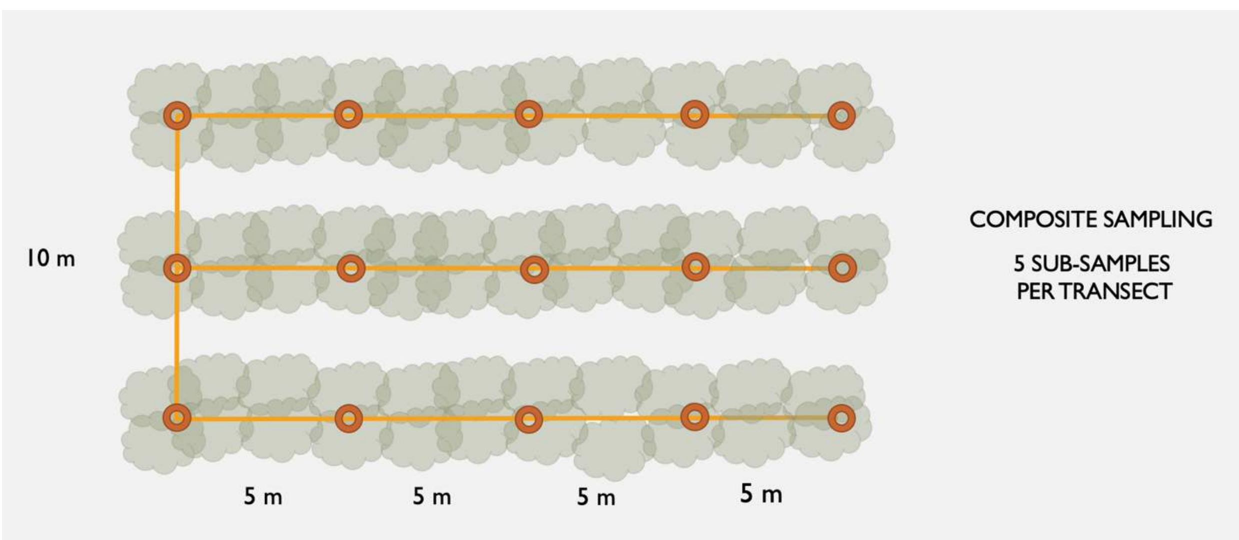


Figure 2 Field sampling scheme used at each field (2 per farm, Field A and Field B). Each field had three samples. To sample each field, we created three transects along the vegetable row crops (We avoided edge effects). Each transect consisted of 5 composite samples, spaced 5 meters apart.

Lab Analyses

Fresh field samples were returned to the lab, sieved at 4 mm, and then either air dried or extracted with 0.5M K_2SO_4 (and subsequently frozen). To date, we have measured bulk density, soil water holding capacity, total inorganic N, net mineralization and nitrification, and permanganate oxidizable carbon (POX-C) across all samples (Culman et al. 2012). In late Fall 2020, we still hope to measure total soil proteins, potentially mineralizable nitrogen (PMN), and soil microbial C and N demand.

To measure gross soil N mineralization and nitrification rates, we set up ^{15}N isotopic pool dilution experiments (Yang et al. 2017, Burger & Jackson 2003, Bowles et al. 2015). These experiments consisted of a standard procedure: ^{15}N-ammonium and ^{15}N-nitrate were evenly mixed with subsamples of each field soil sample; after 24 hours, a subsample was extracted with K_2SO_4 to measure ^{15}N in ammonium and nitrate via diffusion. Another subsample was fumigated with chloroform for microbial biomass.

To date, we have received the results for our first batch of measured isotope samples from the UC Davis Isotope Facility. Based on these initial results, we have proof of concept that the assays worked; we are now confident that the N pool dilution protocol that we developed works, and so we plan to process remainder samples in the coming months. Due to COVID-related, California wildfire air quality-related, and power shut off-related delays, we have not been able to complete this key dataset; similarly, as well as due delays with the arrival of our total organic carbon / total nitrogen (TOC/TN) analyzer, we have not been able to start our microbial C and N demand analyses. The instrument is slated to arrive in November, at which time we will complete these analyses.

Because of the limited samples we have been able to process, our statistical analyses have been limited; as a result, we have not yet had the opportunity to develop the decision-support tool (DST) as originally planned. For now, we have focused efforts to finish processing the remainder of the soil analyses. This process continues to be very limited and slow; for context, UC Berkeley halted all research beginning March 2020; in July 2020, research was permitted to resume but undergraduate researchers were not allowed to assist and personnel were limited to 25% of capacity in research spaces. In addition, other lab facilities, such as the Stable Isotope Facility at UC Davis, were also affected and now have a backlog of samples.

Farmer involvement

Farmer involvement was central to the project's research design and was facilitated by Co-PI UCCE Small Farms Advisor Margaret Lloyd's close relationship to the Yolo County organic farming community. As mentioned, we involved farmers in the site selection process and iteratively co-designed best sampling practices to ensure both site-specificity and consistency across all working farms that we sampled. We also hosted a series of farmer spotlight series, where we paired farmer experts and research experts on a variety of on-farm diversification practices (see below) and invited the broader farming community to listen and participate in a guided open discussion.

Our first farmer spotlight focused on cover crops (“*Successful cover cropping on any farm”*), and provided a Yolo County-specific conversation on the mechanics, applications, benefits, challenges, and economics of cover cropping. The second farmer spotlight centered the importance of soil microbes on farms (“*Demystifying on-farm beneficial microbes”*); based on farmer feedback, we decided to have a whole panel of farmer experts and research experts to provide a variety of perspectives on our still evolving knowledge of soil microbes. Again, due to the COVID-related restrictions and the intense (ongoing) summer and fall harvest season for farmers, our third farmer spotlight has been postponed for early winter. This spotlight will focus on water management from one farmer and one researcher, and will most likely be held via Zoom.

5. RESULTS

Based on both initial and in-depth interviews with farmers in the study, we developed a ranked system for varying levels of diversification on each of the 13 farms sampled. Using the metrics outlined in Figure 1 (ie, crop diversity, crop rotation, and the rate, frequency, and timing of various diversification practices), we ranked each farm from low to high diversification. We found that farm size had no bearing on the level of diversification. For example, Farm 1 (Lowest level of diversification) is a 1,000+ acre operation, while Farm 2 (Second lowest level of diversification) is a 1 acre operation. Farm 14, the Russell Ranch Sustainable Agriculture Facility, served as the control to our above definition of diversity. The control represents the lowest level of diversification among all farms sampled, in terms of crop diversity, crop rotation, and ranked diversification practices.

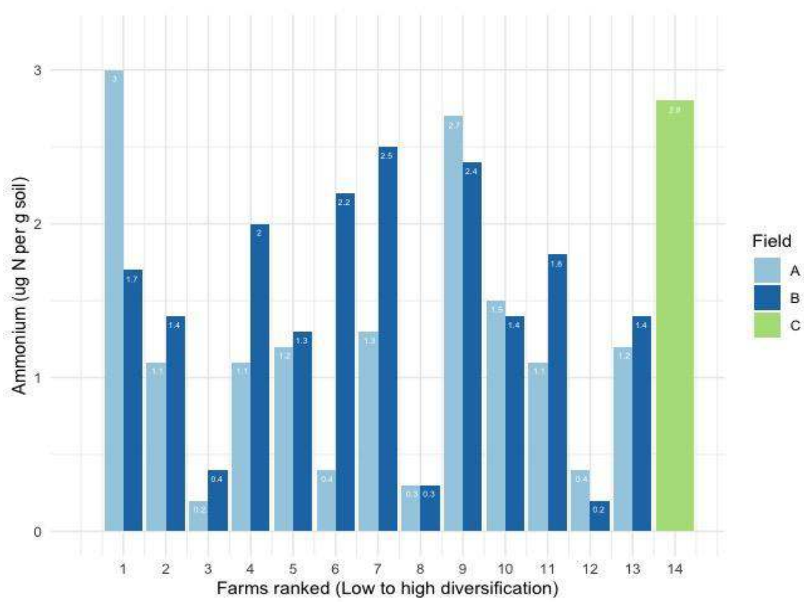


Figure 3 Here we compare ammonium (in ug N per g soil) across a spectrum of diversity among organic farms. The light blue bars represent Field A, the field with the most soil health improvements. The dark blue bars represent Field B, the field with the least soil health improvements. The green bar represents our control, the lowest diversity organic farm, sampled from the Russell Ranch Sustainable Agriculture Facility in Davis, CA.

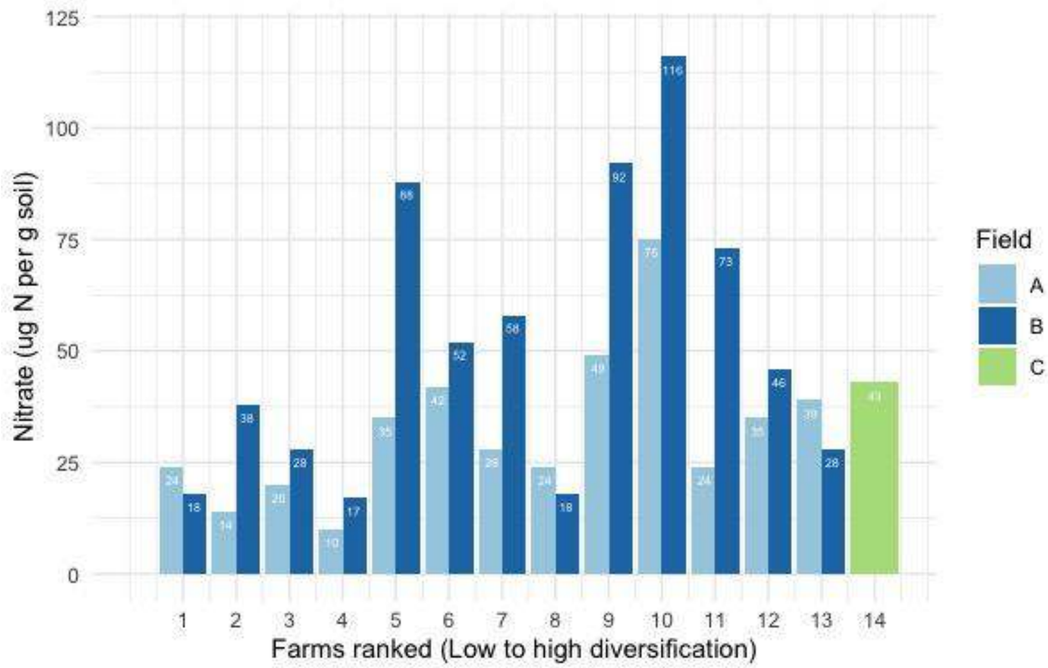


Figure 4 Similar to Figure 3, we compare nitrate (in ug N per g soil) across a spectrum of diversity among organic farms. The light blue bars represent Field A, the field with the most soil health improvements. The dark blue bars represent Field B, the field with the least soil health improvements. The green bar represents our control, the lowest diversity organic farm, sampled from the Russell Ranch Sustainable Agriculture Facility in Davis, CA.

Based on total inorganic nitrogen results (Figure 3 & 4), in general all organic farms across varying levels of diversity had very low ammonium levels (< 3 ug N per g soil). Among the lower ranked diversification farms (Farms 1-7), Field B (Least investments in soil health) had consistently higher levels of ammonium compared to Field A (Most investments in soil health) across farms, with the exception of Farm 1. Among the higher ranked diversification farms, ammonium levels in Field A tended to be higher. For total soil nitrate, across all levels of diversification, most farms had higher levels of nitrate in Field B compared to Field A. Though weakly correlated, Figure 5 shows a positive correlation between levels of diversification and labile carbon.

In the next 3-6 months, we hope to obtain results from all originally proposed datasets, including gross N mineralization and gross N nitrification rates. As Figure 6 depicts, we hope to link various ecosystem services that soil provides on these working farms (based on soil health indicators) to the level of diversification observed across each farm. The right graph proposes several possible trajectories for comparing labile carbon with final gross N mineralization and gross N nitrification rates.

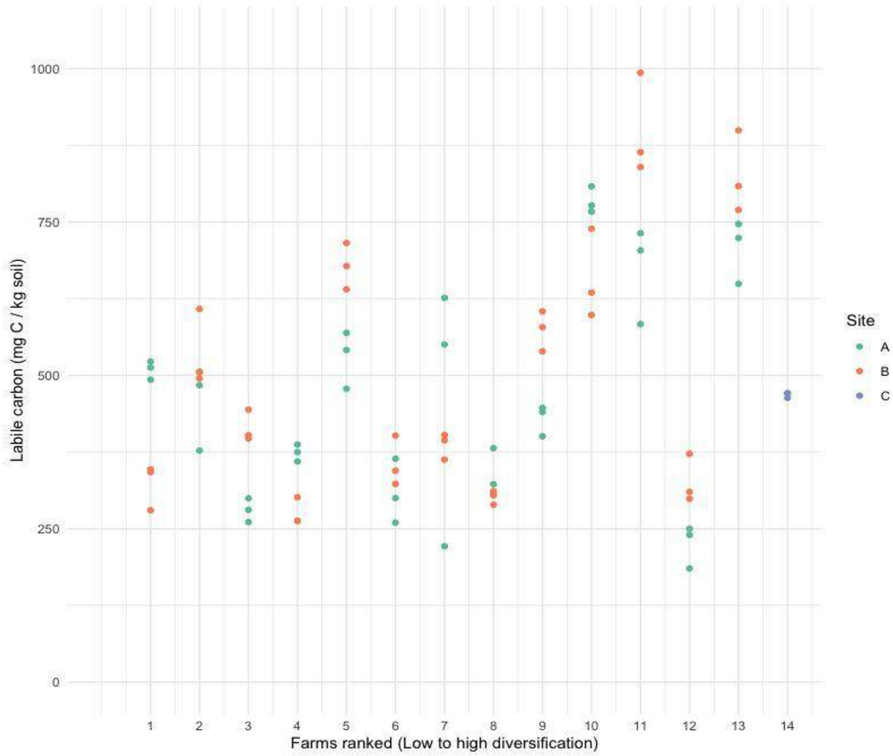


Figure 5 A comparison of labile carbon (in mg C / kg soil) with diversification across all organic farms sampled. The green dots represent Field A, the field with the most soil health improvements. The orange dots represent Field B, the field with the least soil health improvements. The three purple dots represents our control, the lowest diversity organic farm, sampled from the Russell Ranch Sustainable Agriculture Facility in Davis, CA.

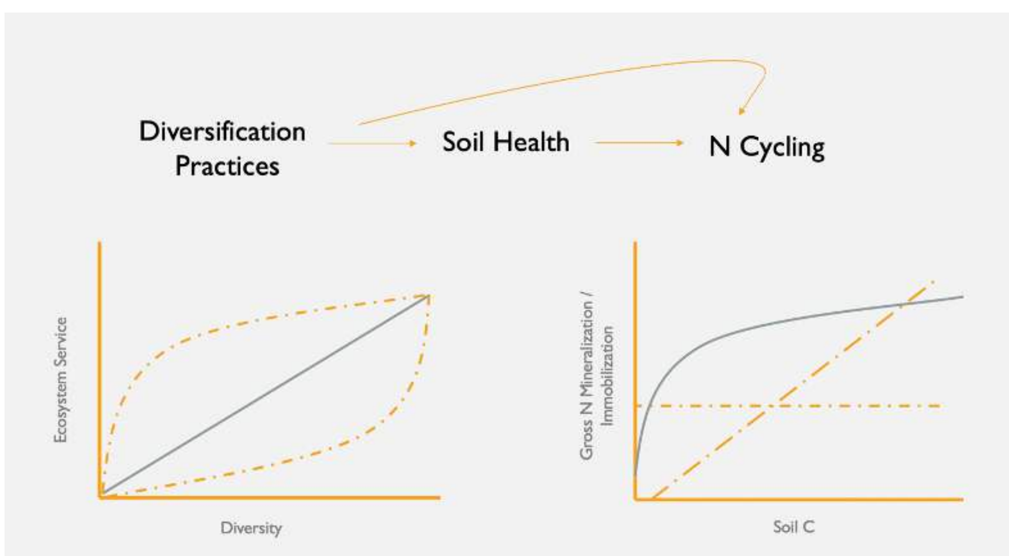


Figure 6 Our anticipated results; conceptually, we aim to link diversification practices to N cycling rates observed in the soil. As the right graph shows, we anticipate soil carbon positively correlates with gross N mineralization and immobilization.

6. CONCLUSIONS

The preliminary results of this project reinforced the initial hypothesis that organic farms in Yolo County exhibit highly variable inorganic nitrogen levels during vegetative growth phases for summer crops. As mentioned in the proposal, these data will complement the gross N mineralization and nitrification data once completed and provide information on the variation of N flows across different systems of farm diversification. The labile carbon results, which show a weak positive correlation between level of farm diversification and active carbon, also present an interesting initial finding; the results suggest a relationship between active soil carbon and on-farm diversity.

We believe the final results of this study will be useful to farmers. A large number of farmers in the study have contacted us inquiring about final results. The slow turnaround time for providing farmers with timely data has been a large limitation of this study. Other than environmental problems related to COVID-19, the very low density budgets required at UC Berkeley, the California wildfires and associated smoke, we encountered very few problems. We were very lucky to collaborate with a willing and extremely cooperative community of farmers for this project.

Based on what we've learned so far, we would also like to compare *gross* N mineralization and nitrification rates with *net* N mineralization and nitrification rates in order to model how these two rates relate to total inorganic nitrogen in soils. The latter data are much easier to measure and more readily available compared to gross and net N rates. As touched on previously, farmers are particularly interested in knowing rates of N processes rather than static pools of N in their farming systems in order to better practice more efficient fertilizer application.

7. OUTREACH

As mentioned in the Methods section, the outreach component was central to our project and its design. Unfortunately, due to the COVID-19 outbreak, we were limited in our ability to realise all of the components of the outreach activities originally planned. We were able to hold two of our three Farmer Spotlight Series, which were a huge success. Both events had a turnout of 50+ farmers (Organic and non-organic), agricultural industry specialists, and general interest participants. We plan to hold one final Farmer Spotlight Series event on December 15, 2020 entitled "Water: Doing more with less," once farmers have more time post- farm season but before the holidays.

Due to the limitations of the COVID-19 outbreak, we were not able to hold our hands-on learning days, as originally planned. However, we were able to put greater focus and energy into making the proposed podcasts. We are currently working on finishing two podcasts in collaboration with the Farmer's Beet, an agricultural centric podcast hosted by the Community Alliance with Family Farmers. The first podcast, which focuses on the pros and challenges of compost application on farms, is in post-production and will be released before the end of the year. This podcast features interviews with several farmers, including one organic farmer from the study. The second podcast will focus on on-farm nitrogen and will share some of the results of this study. We plan to release this podcast by Spring 2021.

At this juncture, we also plan to make a short, informational video once we have compiled and analyzed all the data from the interviews and soil samples. We hope this form of research dissemination will provide a lasting roadmap for farmers to reference. The video will be accompanied by an adjoining factsheet that summarizes key trends and findings.

8. FINANCIAL ACCOUNTING

Please see attached spreadsheet.

9. LEVERAGED RESOURCES

We have not obtained other funding to continue or expand on this project yet. However, PI Bowles plans to seek an OREI grant within the next two years, in part based on results from this project.

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11. PHOTOS

Undergraduate assistants field sampling in July 2019.

Farmer Spotlight #1, on the benefits of cover cropping, held in Woodland, CA with organic farmer Jim Durst and researcher Eric Brennan.

Audience members at Farmer Spotlight #2, on beneficial microbes (top).
Panelists, including research and farmer experts, after the second Farmer Spotlight event (bottom).


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