Agroecological approaches to warm-season cover cropping in northern climate vegetable systems and building collaborations with farmers

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Abstract

Summer cover crops are a management tool that vegetable farmers can use to counteract the negative effects of soil degradation by physically protecting soil, contributing biomass to soil organic matter (SOM), suppressing weed growth, and enhancing nutrient cycling, but their use may be limited in the short growing season of northern climates. Evaluating the effects of cover crops on soil nutrient cycling and SOM in northern climates is an opportunity to collaborate with farmers, which is important because such collaboration improves the quality of knowledge gained from research by recognizing the incompleteness of any single perspective. Collaborative and participatory research is also a means to address the unequal power dynamics in agriculture that have systemically disadvantaged immigrant and minority farmers through interlocking challenges accessing capital, land, and information. In this dissertation, summer cover crops were evaluated in collaborative on-farm trials in northern climates for their ability to accumulate biomass, suppress weeds, affect soil C and N pools, and contribute to fall cash crop yield. Additionally, this dissertation includes a qualitative analysis of existing collaborative relationships between members of a local immigrant farmer cooperative and representatives from Extension, the Department of Agriculture, and a local agricultural non-profit. The summer cover crop trial consisted of four cover crop species treatments, grown for 30 (SD) or 50 days (LD) alongside bare fertilized and unfertilized control treatments: buckwheat (*Fagopyrum esculentum*) and sunn hemp (*Crotalaria juncea)* monocultures, and biculture of chickling vetch (*Lathyrus sativus)* or cowpea (*Vigna unguiculata*) with sorghum-sudangrass (sudax) (*Sorghum bicolor x S. bicolor var. Sudanese*). To quantify cover crop quantity, quality, and weed growth and seed set suppression capability, we measured cover crop and weed biomass and biomass C:N. To quantify effects on cash crops, we measured fall broccoli yield and biomass. Soil N and C cycling were quantified at cover crop peak growth (directly before termination) and one week after cover crop termination for mineral N, PMN, organic N, POX-C, extractable organic C, as well as fluorescein diacetate hydrolysis (FDA) as a proxy for microbial activity to contextualize the other measurements. Cover crops produced biomass consistent with that of more southern climates but legumes did not grow well and did not overcome weed pressure. All cover crops contribute to nutrient retention but not fertility benefits and negatively impacted fall cash crop yield. Collaborative relationships with farmers were dependent on external institutional support, and food systems professionals differed in whether they adopted an equity or equality lens.

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CHAPTER 1. REVIEW OF LITERATURE

Introduction

Soil degradation as a result of agricultural production is an international problem, with biophysical, social, and political implications for food production, rural livelihoods, air and water quality, and climate change. There is no single best practice for maintaining and improving soil quality within agricultural production systems because of the multidimensional complexity and unique characteristics of different farms, as well as the multiple stakeholders in a given location, whose interactions are often characterized by conflicting priorities and unequal power relationships. Given the impossibility of panacea solutions to these types of complex problems, there is increasing interest in local, participatory projects that bring together multiple forms of knowledge and expertise to evaluate tradeoffs. This has been my approach to the project undergirding this thesis: a collaboration with immigrant farmers to assess the viability of summer cover crops as one means of improving and maintaining soil quality in vegetable productions systems. This project develops knowledge about cover crop use and management, and through participatory research methods, valorizes non-academic knowledge about soil quality and vegetable rotation management, and seeks to find more elaborates on mutually beneficial and respectful ways for the university and non-academic partners to engage with one another.

In Minnesota and elsewhere, research to address soil quality questions has been primarily focused on biophysical challenges: reduced tillage, crop rotations, and cover cropping all show promise for various farm contexts (SARE CTIC, 2017). Tillage reduction has been the primary focus for improving soil, with some success worldwide, notably in the USA and Brazil (FAO and ITPS, 2015). In spite of these efforts, the Food and Agriculture Organization of the United Nations reports that farmers in the USA alone spend approximately 33-60 billion dollars on nitrogen (N) and 77-140 billion dollars on phosphorus per year to replace nutrients lost through production practices. Cover crops have gained prominence as means to enhance the ecosystem services in agricultural systems, through prevention of erosion and soil nutrient loss, as well as to improve soil fertility, biodiversity, water holding capacity, and increased farming system resilience (Ding et al., 2006; Bulan et al., 2015; Blesh, 2018; Bowles et al., 2020).

The ecosystem services provided by cover crops can help address the degrative impacts of the intensive practices that characterize vegetable farming systems (Haynes and Tregurtha, 1999). The wide variety of vegetable crops, each of which is grown for a distinct period of time, allows for multiple opportunities to use cover crops to achieve particular benefits, which as been examined most often in organic systems (Robačer et al., 2016). Current expansion in vegetable production is primarily occurring in low-input and organic systems. In Minnesota, the number of organic farms grew by almost 13 percent between 2011 to 2015; organic production nationwide is one of the fastest growing segments in agriculture (Organic Trade Association, 2016). As the demand and production of organic produce rises, more research is needed to address the challenges of soil quality in organic vegetable production, and cover crop research is a promising research avenue. This is particularly true for new entry farmers, many of whom are immigrant and minority producers and who face intersectional barriers to land, capital, and knowledge (Carlisle et al., 2019). Forecasts about the future of Minnesota's workforce indicate that immigrant workers and business owners are an essential component of a healthy Minnesota economy, and that their importance and influence will continue to rise (Allen, 2017). It is therefore of particular importance to work with this expanding demographic when addressing questions of soil quality in Minnesota.

Mixed vegetable production that includes fall-harvested crops may preclude sufficient growth of a fall-seeded cover crop since vegetables often occupy the time and space needed for cover crop establishment. Similarly, cool season vegetable crops can be planted in the early spring before overwintering cover crops reach maturation. In order to maximize cover crop benefits within the complex rotational schedule of vegetable growers, one option may be to grow cover crops within the main growing season. One underexplored opportunity is to take advantage of a natural mid-summer gap between spring and fall vegetable production by planting quick-growing, heat-tolerant cover crops. Previous research has shown that there are multiple legume and non-legume cover crops that are well-suited for quick summer growth (Creamer and Baldwin, 2000; Brainard et al., 2011; O'Connell et al., 2015a). However, in northern climates, the average frost-free season can be as short as four months, which often precludes planting cover crops and cash crops during the same season. Given the short growing season, the soil quality and nutrient cycling effects observed due to cover crops in other locations may not be observable in northern climates.

Collaborative approaches to agricultural research such as the effectiveness of cover crop is important to make sure that the research addresses farmer needs. Agroecology is an approach to agricultural knowledge production that explicitly works to integrate biophysical, social, and political factors, and has been developed as a participatory research model. These approaches have been important for advancing numerous strands of research that would not be possible without farmer input. For example, agroecological research at the Agroecology and Livelihoods Collaborative in Vermont, and through the Center for Agroecology and Sustainable Food Systems at UC Santa Cruz, among others, have found that agroecological collaborative work with farmers facilitates better question formation and results in more applied and feasible answers. In Minnesota, the Regional Sustainable Development Partnership program through Extension and the Forever Green Initiative are both working to create more participatory and interdisciplinary research and practice communities around questions of agriculture and rural livelihoods. Development of collaborative research on summer cover crops through the lens of participatory methods in agroecological research can contribute to these other strands of research and will provide vegetable producers with more knowledge of how to improve soil quality in the Upper Midwest.

Summer cover crop basics

A small but growing body of work exists on summer cover crops. Summary studies as recent as (Robačer et al., 2016), which outlined the current use of cover crops in organic systems, indicate that further research is needed to understand their effects on soil fertility. However, existing research indicates that summer cover crops may be a promising tool for vegetable producers for a variety of reasons, including the improvement and maintenance of soil health.

Contrary to winter cover crops, summer cover crops do not need to be cold hardy, nor have a dormancy period. They are valued for quick, vigorous growth and the ability to withstand high temperature and low moisture conditions. Summer cover crops were also tested for their ability to suppress weed and other pest populations, including nematodes, and for their potential contributions to soil fertility, especially soil N. Most of the potential summer crops are native to tropical regions, and many trials of summer cover crops have taken place in subtropical locations, where year-round vegetable production is common. The most commonly researched summer cover crops are sunn hemp (Wang et al., 2006, 2014; Schomberg et al., 2007; McSorley et al., 2009; Skinner et al., 2012; Boyhan et al., 2016), cowpea (Creamer and Baldwin, 2000; Fitzgerald et al., 2001; Wang et al., 2003, 2006; Brainard et al., 2011; O'Connell et al., 2015b; Boyhan et al., 2016; Kruse and Nair, 2016), both of which are leguminous, and sorghum-sundangrass (Creamer and Baldwin, 2000; Fitzgerald et al., 2001; Wang et al., 2006, 2008; Finney et al., 2009; Brainard2011a; O'Connell et al., 2015b; Boyhan et al., 2016; Kruse and Nair, 2016), which is not. Other legume cover crops include velvet bean, lablab, sesbania, and soybean. Other non-legume species include buckwheat and millet. Summer cover crops are usually grown for 2-3 months in vegetable rotations, often with cash crops planted both before and after the cover crop. In some cases, the cover crop is terminated in strips, and left as a living mulch between cash crop rows (Sarrantonio, 1992; McSorley et al., 2009; Wang et al., 2014), or left as a surface mulch instead of being tilled into soil (Fitzgerald et al., 2001; Finney et al., 2009). The short growth time (compared with 4-6 months of growth for overwintering cover crops) is possible because summer cover crops are grown during the longest days of the year.

Biomass accumulation and subsequent contribution of cover crop to cash crop fertility is an important reason for farmers to use cover crops. Because of the time of year during which summer cover crops are grown, they can accumulate a tremendous amount of biomass in a very short period. For a legume crop, sunn hemp has been shown to produce over 10,000 kg ha^{-1} in as few as 90 days (Schomberg et al., 2007; Stute and Shekinah, 2019). Among non-legume species, sorghum-sudangrass produced high levels of biomass, ranging from ~7200 kg ha^{-1} to almost 9000 kg ha^{-1} with a growing time of 36-75 days (Creamer and Baldwin, 2000; Brainard et al., 2011). In mixtures of legumes and grasses, total biomass was somewhat variable; at the higher end, it was similar to that of grass monocultures (7000-10000 kg ha^{-1}), but some mixes resulted in less than 5000 kg ha^{-1} (Creamer and Baldwin, 2000). Because most summer cover crop research has been conducted in Plant Hardiness Zones 6-10, the biomass potential may be higher than for northern climates, which have fewer growing degree days (GDD). While previous studies with winter cover crops have shown that the ratio of carbon (C) to N in cover crop biomass should be less than 25:1 to avoid N immobilization (Paul, 2007), summer cover crop residue did not cause immobilization, even at higher rates (Wang et al., 2006; O'Connell et al., 2015b; Kruse and Nair, 2016).

Cover crops can be used to suppress weed growth, both by physically competing with weeds while growing, and by releasing allopathic substances into the soil that inhibit weed growth. Summer cover crops that are best suited for weed suppression are those that accumulate significant biomass quickly, in order to physically suppress weed growth. In general, non-legumes are better for weed suppression. A 2016 study of legume and non-legume cover crops planted before fall broccoli found that all cover crops had fewer weeds than a weedy control, but that buckwheat has significantly fewer weeds than grass and legume cover crops (Kruse and Nair, 2016). A 2011 evaluation of summer legume crops with and without grasses concluded that non-legume cover crops were a less expensive and less risky choice for growers whose primary goals were weed suppression (Brainard et al., 2011). However, there can be some problems with grasses interfering with the following cash crop production when not adequately terminated, which can be a particular problem in no-till systems (Finney et al., 2009).

Effects on cash crops

Summer cover crops have generally been followed by higher cash crop yields, though the results vary widely based on cover crop and following cash crop species. Many vegetables crops grown after cover crops result in higher yields, though there was significant variation in the magnitude of increased yield (Wang et al., 2006; Tian et al., 2009, 2011a; Boyhan et al., 2016). There is also some evidence that legume cover crops contribute to higher cash crop yield over non-legume cover crops (Wang et al., 2008), though one study found inconsistent benefits from some cover crops, and detrimental effects from sorghum-sudangrass (Kruse and Nair, 2016). A recent study on summer cover crops in a diverse full-year vegetable rotation showed that yields increased over the 3 years of the study, which could have been due to repeated use of cover crops, but was attributed to increased grower knowledge (Boyhan et al., 2016).

Effects on soil properties

One of the main benefits of summer cover crops is their potential to provide fertility to subsequent crops despite growing for a short period of time. Legumes, because of the symbiotic relationships they can form with N-fixing rhizobia, are particularly useful for this purpose. Measurements of soil fertility mainly focus on the presence and quantity of soil N, which is reported as mineral N (MinN), potentially mineralizable N (PMN), total N (total N), and organic N (EON or DON) and indirectly, through cash plant yield in the absence of additional fertility. In summer cover cropping systems, legume cover crops resulted in significant extractable soil N spikes following termination, which occurred within 10 days of termination (Kruse and Nair, 2016). However, N levels then continued to rise, and peaked at 35 days. Other studies have also suggested long N mineralization periods (Parr et al., 2011). Other studies measured the percentage of N in cover crops, and found that legumes had N concentrations between 2-3%, as did buckwheat, while sorghum-sudangrass had 0.96% N content (Fitzgerald et al., 2001). However, there is wide variation on the amount of nitrogen these crops provide to the soil; one study found that sunn hemp could provide 135-285 kg ha^{-1} N when grown for 120 days, but that N contributions of ~85 kg ha^{-1} and ~195 kg ha^{-1} were possible after 30 and 60 days or growth, respectively (Schomberg et al., 2007). Other studies have shown anywhere from 28 kg ha^{-1} for grass to 168 kg ha^{-1} for legumes, (Fitzgerald et al., 2001; O'Connell et al., 2015b).

Microbial populations have been found to be responsive to seasonal variation, independent of cover crop use. Cover crops generally increase microbial biomass (Mendes et al., 1999; Smukler et al., 2008; Thomazini et al., 2015), and summer cover crops can result in increased microbial enzyme production and carbon use (Tian et al., 2011a). However, few studies have focused on the effects of summer cover crops specifically on soil microbes and microbial processes. In the few studies that do exists, the species selection may play a large role in determining the effect that summer cover crops have on microbes (Tian et al., 2011b).

Identified challenges of summer cover crops

Despite the observed benefits of cover crops and their potential to fit well into the summer fallow period in vegetable production systems, there are a multiple potential pitfalls. Allelopathy is a major concern because many summer cover crop species have allelopathic effects on some subsequent crops, and particularly because many summer cover crops are unfamiliar to growers, and management strategies that work for winter cover crop may not work with summer species (Skinner et al., 2012; Kruse and Nair, 2016). Additionally, species selection is a significant consideration for summer cover crops; while legumes have potential to provide fertilization to fall cash crops, the cost of legume seed may not be warranted if the cover crops are primarily being used for weed suppression or soil coverage and the growing time is not long enough to garner significant N fixation.

Agroecology as an approach to complex agricultural questions

The field of agroecology was initially advanced in the USA as a means to apply ecological principles to agricultural production, with the goal of creating more sustainable agricultural ecosystems (Altieri, 1987). Since its inception, however, it has expanded beyond its agricultural-ecological roots to be understood as a tripartite conceptualization: a scientific theory, a social and political movement, and a set of grounded practices (Wezel et al., 2009; Méndez et al., 2013). Expanding from this definition, agroecology has been argued to be a necessarily transdisciplinary, participatory, and action-oriented approach to complex problems, and one that is most effective when those three strands are combined. There is, however, considerable variation in which of the three strands are integrated in any particular project, and tendencies to focus on some strands more than others are location specific (Wezel et al., 2009).

Agroecology's development into a transdisciplinary field from more narrow disciplinary agricultural research follows the pattern of other interdisciplinary endeavors, such as the development of critical physical geography (Harvey, 1972; Lave et al., 2014; Lane, 2017), applied economics (Batie, 2008), and political ecology (Zimmerer, 1994). As in other disciplines, agroecological approaches have encouraged question formation that incorporates social, historical, and political contexts, as well as a reconsideration of agricultural production paradigms in various sub-disciplines including soil science, agronomy, international agriculture, and sustainability studies (Bland and Bell, 2007; Bell et al., 2008; Giller et al., 2009; Basche et al., 2014; Duru et al., 2015; Tittonell, 2016). Agroecology has also been a useful framework by which to better understand the complex set of factors that influence how farmers interact with each other and the resources that they manage. Agroecological studies of farms and rural landscapes have found that social and political factors are as important as biophysical conditions in determining optimal future land use (Jordan et al., 2016a). Research in weed science has also found that question formation and research using an agroecological lens yields answers and potential avenues for further research that would not be considered without that lens (Jordan et al., 2016b). These approaches have also aided a more nuanced understanding of farmers' interactions with soil. Interpersonal relations, economic incentives, and larger food-system factors, in addition to knowledge about soil quality and methods for managing soil sustainably, all influence soil management practices (Carlisle, 2016; Roesch-McNally et al., 2017). The multidisciplinary lens of agroecology can lead to better question formation and research results beyond what is possible from a purely agronomic perspective.

The participatory aspect of agroecology manifests in distinct ways in different types of research. Participatory research itself has a long history beyond agriculture, as a means for communities to work for change, far beyond the scope of research methodology (Pain and Francis, 2003). Additionally, participatory research challenges many of the strictly positivist tendencies in agricultural research; the development of participatory action research has been described as a movement to address, among other problems, the presumption of perfect objectivity that pervades scientific inquiry (Fals Borda, 2001). Even so, the non-academic and academic collaboration facilitated through participatory approaches has allowed for significant progress on agroecological questions around the world. For example, models of climate change adaption are improved when farmers are recognized as improvisational agents in their agricultural context (Crane et al., 2011); effective means to mitigate soil erosion and associated vegetable productivity declines in the Philippines was enabled via farmer-research collaboration (Poudel et al., 2000); a review of SARE funded projects in 2001 found that much farmer knowledge is exchanged via informal knowledge networks, and that researchers do not have access to these networks without working directly with farmers (Kroma and Flora, 2001); others have come to similar results in various farming contexts (Fliert and Braun, 2002; Snapp et al., 2005; Bruges and Smith, 2008; Lyon et al., 2010).

In the United States, land-grant universities (LGUs) and their associated agricultural extension services have been one of the primary mechanisms for participatory and collaborative research and knowledge sharing, despite foundational issues that make the LGU system inaccessible and unwelcoming to many. The LGU system, established in the mid-1800s, was an innovation in democratizing education through their tripartite mission of teaching, research, and extension, though notably, gender and racial inequality were, and continue to be, endemic to the LGU system (Herren and Edwards, 2002). Furthermore, the land on which universities have been constructed and which paid for formation of the system, was expropriated from indigenous people over the course of the 18th and 19th centuries (Lee et al., 2020). In the 20th century, the role of extension has been primarily as a technical information source (Heleba et al., 2016). More recently, however, partly in recognition of the ongoing issues with LGUs, there have been efforts reconsider the historic and future role of extension (Peters, 2014) and even think of extension as a way to co-create agroecological knowledge between researchers and farmers (Warner, 2006).

Agroecological approaches to cover cropping

Agroecological studies of how and why farmers do (or do not) use cover crops and their viability in distinct farming systems have painted a complex picture of interconnected factors that promote and inhibit cover crop use. Studies have shown that beyond the biophysical factors on which cover crop research often focuses, political and social factors significantly affect perceptions about cover crops and whether farmers will adopt cover cropping practices (O'Connell et al., 2015a; Moore et al., 2016). However, it is highly variable which factors influence farmers in a given community. While long-term studies of agroecological systems indicate that cover crops may play an important role (Jackson et al., 2007), more agroecologically-focused research is needed to assess cover crops in specific contexts, in collaboration with farmers.

Identified challenges to participatory work

Significant challenges exist in the implementation of agroecological PAR. Many studies assume an increased time investment for conducting participatory research, though without evidence. An additional concern for the scientific community is how to balance scientific rigor with farm-applicable practices, though both can be ameliorated through collaboration with farmers, and by use of particular research designs such as the mother-baby research plot design (Poudel et al., 2000; Snapp et al., 2005; Bruges and Smith, 2008). Another challenge of PAR is how to define what participation means, when it is necessary, and how it should take place. PAR literature specifically cautions again skipping the "preflection" step of getting to know non-academic stakeholders and developing relationships (Méndez et al., 2017).

Others argue that the most important part of PAR is the recognition of power dynamics and constraints resulting from them, and that full participation of all stakeholders from the beginning is too rigid a requirement for PAR (Lyon et al., 2010). In a multi-year study of rotational grazing systems, researchers found that they received better input from farmers and were able to improve and refine their research questions only after developing trust and credibility with the farmers. Additionally, the researchers deliberately stopped using formal presentation materials in favor of field walks and roundtable discussions with farmers, because they felt introduction of academic formal presentation materials inhibited conversation. Definitions of participation are further complicated in that farmers and researchers may, and often do, approach projects with divergent priorities and interests. In one of two state-funded agroecology projects, farmers and researchers co-developed a nitrate monitor (Bruges and Smith, 2008). For farmers, this tool was useful because it potentially allowed them to apply less fertilizer; for researchers, it was important because it might train farmers to be more conscious about their contributions to nitrate pollution. Because the monitor was developed and used, both groups felt the project was successful. However, researchers worried that farmers were solely concerned with the economic benefits of the monitor, and thus they would not sustain use of the environmentally friendly management tools if the economic incentives were to disappear.

Conclusion & Chapter Overview

Cover crops in vegetable systems can provide multiple ecosystem services and respond to farmer-identified challenges. Participatory research to build agroecological knowledge is key to food systems transformation and can address broader systemic issues beyond the specific research topic. The purpose of this dissertation is to advance knowledge of summer cover crops in vegetable systems while also contributing knowledge about participatory and collaborative work between farmers and non-farmers. Chapter 2 describes the agronomic aspects of summer cover crops: their biomass accumulation potential, weed suppression capability, and effect on cash crop yield. Chapter 3 investigates the impact of summer cover crops on soil nutrient cycling. Chapter 4 reports on a case study of multiple non-research collaborative relationships between historically marginalized farmers and non-farmers and provides insight into ways to improve collaboration. Chapter 5 provides reflection on the research process as a graduate student balancing the requirements of the university with other ways of knowing.

CHAPTER 2. ECOSYSTEM SERVICES AND TRADEOFFS OF SUMMER COVER CROPS IN NORTHERN REGION ORGANIC VEGETABLE ROTATIONS

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Summary

Intensive production practices characterizing vegetable farming contribute to high productivity, but often at the expense of supporting and regulating ecosystem services. Even in diverse vegetable production systems, further diversification with cover crops may support increased resilience through soil organic matter (SOM) contributions and physical soil protection. Vegetable farming operations often include production during spring and fall, limiting establishment and productive potential of the overwintered cover crops that are more widely used in the USA. In northern climates, warm-season cover crops planted during short summer fallow periods common in vegetable systems could be a tool to build resilience via ecosystem service enhancement. This project evaluated summer cover crops in the northern climatic conditions of MN and WI for their ability to accumulate biomass, suppress weeds, and contribute to fall cash crop yield. Our study included two sites and two years, during which we investigated the effects of four cover crop species treatments, grown for 30 (short duration, SD) or 50 days (long duration, LD) alongside bare fertilized and unfertilized control treatments: buckwheat (*Fagopyrum esculentum*) and sunn hemp (*Crotalaria juncea*) monocultures, and biculture of chickling vetch (*Lathyrus sativus*) or cowpea (*Vigna unguiculata*) with sorghum-sudangrass (sudax) (*Sorghum bicolor x S. bicolor var. Sudanese*). To quantify cover crop quantity, quality, and weed growth and seed set suppression capacity, we measured cover crop and weed biomass, and biomass C:N. To quantify effects on cash crops, we measured fall broccoli yield and biomass. Mean total biomass (cover crop + weeds) by site year ranged from 1890 kg ha^{-1} in MN Y1 to 5793 kg ha^{-1} in WI Y2 and varied among species in Y1 for both the SD and LD treatments. Most cover crops did not outcompete weeds, though cover crops contributed to higher overall biomass than weeds. Data from Y1 show that cover crops were unable to replace fertilizer for fall broccoli yield, and without sufficient time for decomposition, reduced fall crop yield. Y2 broccoli did not reach maturity due to fall freeze. Summer cover crops, because of their biomass accumulation potential, may be used by farmers in northern climates to fit into cropping system niches that have historically been left as bare soil, but care with timing is necessary to optimize weed suppression and mitigate tradeoffs for cash crop production.

Introduction

Intensive production practices characterizing typical vegetable farming focus on maximal cash crop yield (provisioning services) to the detriment of supporting or regulating ecosystem services (Smuckler et al., 2012). Cover crop integration into vegetable rotations can perform supporting and regulating services such as contributing to soil carbon, nitrogen contribution, and pest suppression (Ding et al., 2006; Bulan et al., 2015; Blesh, 2018). Because cover crops increase rotational diversity, they may also provide important contributions to farming systems resilience (Bowles et al., 2020). Cover crop effectiveness is typically measured by the degree of contribution to supporting or regulating services, or indirect effects of maintained cash crop yield (Kaspar and Singer, 2011; Schipanski et al., 2014). Recent surveys indicate increased farmer interest in and adoption of cover crops, with the majority of respondents reporting that cover crops have improved soil health on their farms (SARE CTIC, 2017). This interest is particularly high among organic growers, who are mandated to follow practices that combine soil fertility and pest management with biological processes (Bellows, 2005).

Vegetable farmers often grow multiple cash crops during the growing season, leaving few periods of bare ground and thus limiting opportunities for cover crop use. Across the US Midwest agricultural region, cereal rye (*Secale cereale L.*) and other cool season grasses remain the most common cover crops (Singer, 2008). Cool season cover crops in northern regions require relatively long periods of growth in fall and spring to produce significant biomass, which may not be feasible for vegetable systems in which cash crops, such as greens or broccoli, occupy the spring and fall cropping period. To maximize cover crop benefits within the rotational schedule of vegetable growers, cover crops sown in the main summer season between cool season cash crops may be an opportunity to enhance diversification and benefits from the ecosystem services that cover crops can provide.

Summer cover crops have the potential to significantly enhance regulatory and supporting ecosystem services through biomass production. Cover crop biomass residue can replenish SOM, thus preventing or reversing soil organic matter (SOM) loss over time in agricultural soil (Reicosky and Forcella, 1998; Dabney et al., 2001; Steenwerth and Belina, 2008; Boyhan et al., 2016). Biomass accumulation is usually highest from grass cover crop species, reaching up to 14 Mg ha^{-1} for sorghum-sudangrass (*Sorghum bicolor x S. bicolor var. Sudanese*), also called sudax, grown continuously over the summer (Stute and Shekinah, 2019), or when cut for hay or foraged repeatedly during a single season (Finney et al., 2009). When grown for a short period without cutting, sorghum-sudangrass can still accumulate high amounts of biomass, ranging from 10 Mg ha^{-1} biomass within 66-90 days after planting (DAP) and 7.2 Mg ha^{-1} (O'Connell et al., 2015b) to almost 9 Mg ha^{-1} 36-75 DAP (Creamer and Baldwin, 2000; Brainard et al., 2011). The biomass accumulation of cover crops can suppress weed growth and seed set through competitive effects (Masilionyte et al., 2017). A particularly effective and often-used weed suppressive cover crop is buckwheat (*Fagopyrum esculentum*), because of its quick growth (Kruse and Nair, 2016). Use of summer cover crops for weed suppression may have particular benefits because they grow at the same time of year when weeds are most productive and can set seed in fewer than 60 days (Miyanishi and Cavers, 1980; Brainard et al., 2011). During short-term fallow periods in which a weedy fallow could be terminated before weed seed production, cover crop species are more desirable because of their consistent growth and maturation. Use of cover crops instead of weedy fallows limits accidental contribution to the weed seed bank and future crop-weed interference (Wortman, 2016).

Cover crops can provide fertility to following cash crops through biomass decomposition and release of nutrients. Decomposition of grass cover crop species returns nitrogen taken up during plant growth, while legume cover crops confer an additional benefit of adding fertility through biological nitrogen fixation. Multiple legume cover crop species are well-suited as summer cover crops because of their potential for biomass accumulation and provision of fertility to subsequent crops (Creamer and Baldwin, 2000; O'Connell et al., 2015b). Summer legume cover crops have demonstrated potential to contribute more than 100 kg ha^{-1} new N to following cash crop production, measured by nitrogen derived from the atmosphere (Ndfa) (Büchi et al., 2015), while total N contribution from cover crop biomass can reach 70 kg ha^{-1} for non-legumes, and over 200 kg ha^{-1} in legume-grass mixtures (Parr et al., 2011). Summer legume cover crops such as sunn hemp (*Crotalaria juncea*) have demonstrated potential to produce high levels of biomass while providing new nitrogen to the soil and suppressing weeds (Price et al., 2012). Fertility benefits from cover crops, whether through nutrient recycling from biomass or new nitrogen via legume fixation, may be an important tool for organic farmers to supplement slow-release organic fertilizers while providing the aforementioned ecosystem benefits. However, high cover crop biomass does not necessarily lead to high fertility benefits; the balance of nutrient immobilization and mineralization during cover crop decomposition is affected by existing SOM, microbial activity, and biomass quality, and can therefore result in systems tradeoffs rather than simple benefits.

Combining cover crop species as mixtures can realize multiple benefits based on the complementary characteristics of individual species (Finney and Kaye, 2017). Cover crop mixtures can be particularly effective at weed suppression (Brainard et al., 2011). However, mixtures often produce less total biomass than their component species planted as monocultures (Finney et al., 2016). A key reason to use cover crop mixes is to balance biomass productivity with N fertility, by pairing high C:N grass species with nitrogen-fixing legumes (Finney and Kaye, 2017; Finney et al., 2017).

Limited research suggests that the benefits of summer cover crops, including high biomass, weed suppression, and fertility are achievable even in northern climates (USDA plant hardiness zones 1-4) (Kruse and Nair, 2016; Stute and Shekinah, 2019), though establishment of cover crops and cash crops within the same short season remains challenging. High biomass accumulation of summer cover crops during a short period in the middle of summer would offer farmers a diversification tool to protect or improve soil structure and fertility. However, insufficient growing time could result in cover crops having a negative effect on fall cash crop growth by immobilizing nutrients without building SOM. Our aim was to increase understanding of promising summer cover crop species and mixtures grown in northern vegetable systems within the time constraints of spring and fall vegetable crops, and how the growth of these cover crops might differ between low and medium OM soils. We quantified the degree to which short-season summer cover crops grown in soils with contrasting OM content accumulated biomass and N, contributed to weed suppression, and served as a fertilizer replacement for fall cash crops. We hypothesized that the chosen quick-growing summer cover crops species would provide biomass, fertility, and weed suppression benefits similar to those seen in warmer climates and with over-wintered cover crops, but that the benefits would be limited in soils with low OM content.

Methods and Materials

The experiment was conducted in the summers of 2017 (Y1) and 2018 (Y2) on two certified organic working vegetable farms in MN and WI, both in Zone 4A. The MN soil was a Braham loamy fine sand, measured SOM 11 g kg^{-1}. The WI soil is a Crystal Lake silt loam, measured SOM 23 g kg^{-1}. Cumulative GDD (with baseline 10 C) for the MN site were 416.9 and 545.9 in Y1 and Y2 respectively, and for the WI site, 450.6 and 549.1 in Y1 and Y2 (Figure 2.1).

Between-site management was kept as consistent as possible given the options provided by farmer equipment and normal practice, with a key difference of lack of irrigation capacity at the WI site. In Y1, all cover crops were terminated using a tractor-mounted rotary mower, while in Y2, all cover crops were terminated using a walk-behind flail mower (Table 2.1).

Experimental design and treatments

Each site (MN and WI) used a factorial randomized complete block experimental design with four replicates and two treatment levels. Treatments consisted of four cover crops species and a bare fallow with and without added fertilizer, with each of these four cover crop treatments planted on two dates, representing long and short cover crop growing durations, and two bare control treatments. Cover crop species treatments included two monocultures and two bicultures. Monocultures included buckwheat (*Fagopyrum esculentum*) (75 kg ha^{-1}) and sunn hemp (*Crotalaria juncea*) (38 kg ha^{-1})

and bicultures included chickling vetch (*Lathyrus sativus*) (75 kg ha^{-1}) and sudax (*Sorghum bicolor x S. bicolor var. Sudanese*) 42.6 kg ha^{-1}), and cowpea (*Vigna unguiculata*) (44.8 kg ha^{-1}) and sudax (42.6 kg ha^{-1}). Each experimental unit at MN consisted of a plot 3 m wide and 4.5 m long. In WI, each experimental unit was 3.6 m wide and 4.5 m long. Species treatments were planted on two dates, three weeks apart, to create duration treatments representing realistic available planting windows on typical organic vegetable farms in northern climates. The long duration (LD) planting was seeded in early June following spring arugula harvest. The short duration (SD) planting was seeded three weeks after long duration planting. All cover crop plots were left unweeded throughout growth. Weeds were removed weekly from bare plots. All cover crop plots were terminated on the same date within a site year, 50 DAP for the LD plots and 30 DAP for the SD plots. Soil samples were collected at peak cover crop growth, immediately before termination, and at broccoli transplant, and analyzed for labile C and N via a suite of indicators (Wauters, 2020).

Cover crop biomass

Immediately prior to cover crop termination, two 0.1 m^2 quadrats of biomass were collected from each plot avoiding the edges, and divided by cover crop species (one or two for each treatment) and weeds. Biomass was transferred to a 60˚C oven for at least 48 hours before being weighed for dry biomass yield and then ground and analyzed for C and N content using a dry combustion analyzer (Elementar VarioMax CN analyzer, Elementar Americas). Total biomass N was calculated for each cover crop species via the percentage of N in the biomass.

Cash crop yield

In Y1, the cash crop (Gypsy broccoli) was harvested four times between early October and early November from 16 plants from the center of each plot. Broccoli was graded according to USDA market standards 1 & 2, with all other harvestable heads treated as unmarketable yield. Persistent cold after the first frost, prevented broccoli harvest in Y2; instead, two immature plants were collected from each plot and weighed for aboveground dry biomass.

Statistical analysis

Total biomass, total biomass N, weed biomass, cover crop C:N, and broccoli yield were all modeled using estimated marginal means (EMMs), on a mixed model in which block was a random effect, and species and duration treatment were fixed effects. Due to interactions, each of the four site years was modeled separately except where noted. EMMs were used to account for imbalances in the data caused by missing samples. Biomass, biomass N, and C:N mean separation was calculated using Tukey's HSD on the mixed model, comparing the four cover crop species within a duration treatment. No bare control was included in these models because the bare treatments were kept biomass free. Pairwise comparison was used to assess differences between long and short duration within a single species. Weed biomass as a percentage of total biomass was calculated as a linear, quadratic, and break-point linear regression, with the most significant model chosen for display and discussion. Broccoli total marketable yield from Y1 was modeled across durations, but separated by location due to interactions. Mean separation was calculated using Tukey's HSD on the mixed model with all treatments including the fertilized and unfertilized bare control, as well as on all of the unfertilized treatments compared without the fertilized control. Statistical analysis was carried out using R version 3.6.1, using the *lme4*, *multcomp*, and *segmented* packages for analysis, and *ggplot2* for visuals (Hothorn et al., 2008; R Core Team, 2013; Bates et al., 2015; Wickham, 2016).

Results

Total biomass, N contribution, C:N

Mean total biomass (cover crop + weeds) averaged across duration by site year ranged from 1890 kg ha^{-1} in MN Y1 to 5790 kg ha^{-1} in WI Y2. When separated by duration, total biomass varied among species in Y1 for both the SD and LD treatments (Table 2.2). Specifically, buckwheat in Y1 produced between 37% and 47% more biomass than the next highest treatments in MN, while in WI, buckwheat outproduced the other species by only 6%. In Y2, total biomass did not differ among species for either duration, with total overall biomass generally higher in Y2 than in Y1. Total biomass in WI was roughly double that of MN for both years. Total biomass production for LD was higher than SD for all species in all site years (Figure 2.2A).

Total biomass N contribution followed similar patterns as total biomass among species (Table 1). Mean biomass N averaged across duration ranged from 40.6 kg ha^{-1} in MN Y1 to 153.2kg ha^{-1} in WI in Y2. Despite large total biomass differences between LD and SD, biomass N was similar across duration, due to higher C:N proportion in LD biomass. Biomass N contribution for SD treatments was equivalent across species in three of four site years (Table 2.2).

Overall biomass C:N for all species in all four site years was higher in LD than SD treatments ($p<0.05$) (Figure 2.2B). Averaged across treatment, MN cover crop biomass C:N was 20.0 in Y1 and 31.6 in Y2, both of which were higher than the respective C:N in WI, which were 13.9 in Y1 and 15.8 in Y2 ($p<0.001$).

Weed suppression

Buckwheat suppressed weeds most effectively in LD treatments for all four site years, as well as WI Y2 in the SD treatment (Table 2.2). Buckwheat as a proportion of total biomass ranged from 48% in MN Y2 SD to 95% in WI Y1 LD. The sunn hemp LD treatment resulted in less weed suppression than at least one other treatment in all four site years. Sunn hemp biomass as a proportion of total biomass ranged from complete species loss (mean of 0%) in WI Y2 long duration to 16% in MN Y1 SD. Across species, weed biomass as a proportion of total biomass decreased as total biomass increased up to 2169 kg ha^{-1}(adjusted $r^2 = 0.641$, $p < 0.001$), at 25% biomass (Figure 2.3). There was no significant relationship between total biomass and weed proportion of total biomass beyond 2169 kg ha^{-1} (adjusted $r^2 = 0.0192$, $p = 0.192$).

Cash crop

No cover cropped treatment produced a yield equivalent to that of the fertilized control treatment in Y1 (Table 2.3). When fertilized treatment was removed from the model for comparison of the four species and unfertilized bare treatments, the bare control was 30% higher than any cover cropped treatments in MN ($p=0.062$), and 26% in WI ($p=0.096$). Mean yield across all cover crop species treatments (without the bare control) in MN was 2234.6 kg ha^{-1}, and 8376 kg ha^{-1} in WI. Duration was marginally significant (p=0.061) driven by differences in MN, in which mean yield was 3662.5 kg ha^{-1} in the SD treatment and 2853.9 kg ha^{-1} the LD treatment.

Marketable yield as a percentage of total yield in Y1 differed among treatments within locations. In MN, cover crop duration did not affect marketable yield. Among species, broccoli plants in cowpea & sudax treatments produced a lower percentage of marketable yield than the unfertilized bare control treatment, 10% and 43%of total yield, respectively (p <0.001). Marketable broccoli yield in MN from all unfertilized treatments did not match the percentage of marketable yield from the fertilized treatments (89%). In WI, SD treatments had overall higher percentages of marketable yield than LD, 72% and 83%, respectively (p =0.03). The percentage of marketable yield from all cover cropped treatments was below that of the fertilized control (fertilized control = 94%), though the difference was only significant for sunn hemp (67%, p = 0.02). When comparing cover crop treatments without the bare treatments, MN had lower marketable yield than WI, and the SD treatment had higher marketable yield than LD.

Yield data for Y2 is not included in Table 2.3 due to persistent cold after the first frost, which prevented broccoli plants from reaching full maturity. Dry immature broccoli plant biomass from all five unfertilized treatments (bare and four species) was equivalent to that of the fertilized treatment at WI (fertilized = 183 g, mean unfertilized = 159 g, SE = 29). Dry biomass of plants in MN was higher in the fertilized treatment than in the unfertilized treatments (fertilized = 97.5 g, mean unfertilized = 40.86 g, SE = 8.4).

Discussion

In this study we demonstrated that cover crops grown for short periods in the summer could provide supporting and regulating ecosystem services though high biomass accumulation, but they may do so at the expense of fall cash crop yield, and they produce less biomass of lower quality in low OM soils. Ecosystem service tradeoffs have been well-established for cool-season cover crops in field cropping systems, with greater N retention associated with decreased ability to provide fertility to the system (Finney et al., 2017). In vegetable systems, summer cover crops are often grown for > 2-3 months (Boyhan et al., 2016; Stute and Shekinah, 2019), which can assure high biomass productivity but is longer than many growers can afford to take away from spring and fall cash crop production. In this study, we focused on 30 and 50 growing days, to fit the cover crops into realistic cool season vegetable rotations of northern climates (USDA plant hardiness zones 1-4). Despite the brief growing period, buckwheat and sudax in both mixes accumulated biomass commensurate with that of more temperate climates (Creamer and Baldwin, 2000; O'Connell et al., 2015b). The biomass potential of cover crops after a short period of growth makes them a viable option to enhance the supporting ecosystem services by replacing bare fallows and adding organic matter (Smuckler et al., 2012).

The use of summer cover crops as a diversification tool may be of particular importance to farmers interested in altering cropping rotations due to climate change. For example, the increase in extreme summer precipitation events in MN and WI (Pryor et al., 2014) underscores the importance of soil protection from erosion. It also suggests that summer cover crops may increase the adaptive capacity of farmers who can build soil during a time when cash crops may have time to grow.

Biomass accumulation in the LD treatment was higher than typical cool season cover crop biomass (Kaspar and Bakker, 2015). In WI, maximum accumulation was over five times overwintered cool season grass biomass recorded accumulation of 1.66 Mg ha^{-1}(Kaspar and Bakker, 2015), while in MN, biomass was almost three times the mean cool season cover crop yield (Kaspar and Bakker, 2015). The demonstrated biomass accumulation of the evaluated summer cover crops suggests they may provide contributions to SOM and be an alternative to bare fallow periods even when grown for less than two months.

Biomass differences between the two sites are best explained by variation in soil type and fertility. The MN and WI sites were chosen to test the effects of summer cover crops on distinct soil quality circumstances; the Braham loamy sand soil of MN had 11 g kg^{-1} SOM, requiring summer irrigation. The WI site was a Crystal silt loam with 23 g kg^{-1} SOM on which the farmer had never needed to use irrigation While cover crop performance was predicted to differ between sites, the contrast in cover crop performance was beyond expectation. Low biomass accumulation in MN persisted despite irrigation, which was necessary to promote germination in the sandy soil. Low biomass suggests that, in some instances, cover crops may not be able to provide desired ecosystem services without fertilization. Pairing cover crops with fertility sources is not uncommon. Over-wintered cover crops are often planted in synchrony with fall manure application, such that the cover crop can prevent nutrient leaching from manure (Cambardella et al., 2010; Thilakarathna et al., 2015). Applying fertilizer specifically for cover crop success is mentioned in farmer-focused publications (Clark, 2013), but is lacking in academic literature. While cover crops are touted as a tool for improving poor soil, our results suggest that there may be a soil OM threshold below which cover crops cannot produce sufficient biomass to provide SOM-building benefits unless coupled with synchronous fertilizer.

The need for additional inputs highlights the negative potential of cover crops. Specifically, as has been observed for conservation agriculture practice in the highly eroded soils of sub-Saharan Africa, higher input costs are a necessary pre-condition to implement conservation practices, which excludes them as an option for the poorest farmers, even though these farmers might be farming soils that need the conservation strategy most (Giller et al., 2009). Such a threshold suggests a need for targeted cover crop experimentation in highly eroded and sandy soils to determine the conditions in which diversification via cover crops can deliver ecosystem services such as weed suppression and SOM contribution and when they may result in untenable tradeoffs.

Duration treatment led to strong differences in biomass accumulation in three of four site years, and was reflected in GDD differences, Studies of summer and winter cover crops point to the importance of GDD in determining plant growth (Brennan and Boyd, 2012; Baraibar et al., 2018; Stute and Shekinah, 2019). Lower GDD DAP^{-1}(cumulative GDD divided by DAP) leads to lower overall growth (Brennan and Boyd, 2012). In the US, GDD DAP^{-1} varies widely by season and location, and differs based on the calculated base temperature; the 30-year average GDD DAP^{-1} in MN during the corn growing season (June-October) is 16.9 (baseline 10C) (UMN, 2019).

Much of the GDD accumulation during the corn growing season takes place in the latter part of the summer, so there is concern that in northern regions (USDA Plant Hardiness Zones 1-4), the climate may not provide sufficient GDD even in summer, especially for cover crops planted early in the growing season. Our results for GDD DAP^{-1}ranged from 8.3 to 10.9, confirming that the GDD accumulation at the beginning of the summer is less than at the end. Summer cover crops may be most successful when planted later in the season, after a long spring crop, to take more advantage of GDD during the summer.

Biomass productivity was also heavily dependent on species treatment, indicating the importance of appropriate species selection for specific services. Legumes were included in the study for their potential to fix nitrogen and contribute fertility. However, legume biomass was notably low, limiting the potential for N fixation and associated fertility benefits. The proportion of legume in the total harvested biomass for each of the three legume species treatments (cowpea & sudax, vetch & sudax, and sunn hemp) ranged from 0 to 0.5, and the mean proportion of legumes as part of total cover crop biomass was only 0.07. Seeding rates in the sudax bicultures may have contributed to low legume biomass. Others have found that a legume-sudax mix planted 50%-50% by seed weight resulted in biomass that was 85% grass and 15% legume (Stute and Shekinah, 2019). Our seeding rates were roughly 50%-50% by seed weight for the cowpea-sudax mix (44.8 kg $ha^{-1}$and 42.6 kg ha^{-1}), and due to large seed size, the vetch-sudax mix was 63%-36% (75 kg $ha^{-1}$and 42.6 kg ha^{-1}). The low ratio of legumes to non-legume (grass and weed) biomass suggests that higher seeding rates are necessary to encourage legume productivity, both in absolute terms and as a proportion of the mixture. Future studies should examine chickling vetch and sunn hemp under more optimal conditions. Chickling vetch has demonstrated high potential as a cover crop in drought and high salinity areas (Lambein et al., 2019), and a high potential for N fixation (Büchi et al., 2015). Sunn hemp also has demonstrated high potential for biomass production that was not achieved in this study. This may have resulted from low soil temperatures at planting, although sunn hemp can be planted any time after the final spring frost (Schonbeck and Morse, 2006).

Because of notable biomass differences, cover crop species differed in the ecosystem services provided. Negative cover crop effects on following cash crops have been noted for multiple species, most notably from sorghum-sundangrass (Kruse and Nair, 2016). This study did not provide evidence for species-specific detrimental effects, but suggests that decomposing cover crop residue led to nutrient immobilization, which is confirmed via soil nitrate measurements (Wauters, 2020). Given the high sorghum-sudangrass' high rate of biomass accumulation, it may not be suitable as an immediate precursor to fall vegetables, despite its potential to contribute to ecosystem benefits such as building SOM and physically protecting soil from erosion (Finney et al., 2016). Of all species, buckwheat, which is already a common summer cover crop (Bulan et al., 2015), provided the most consistent combination of weed suppression and growth. Because of its added benefit to pollinators, the success of buckwheat also indicates that it may also be useful to focus on non-fertility benefits of cover crops during short periods in the summer.

Weed suppression services of cover crops are important insofar as they prevent weed seed maturation and subsequent replenishment of the weed seed bank, or through allelopathic effects that inhibit weed growth following cover crop termination. The low weed suppression capability of most cover crops in this study is of concern because some of the most common weed observed in these systems, including *Portulaca oleracea*, *Amaranthus retroflexus*, and *Chenopodium album* have the potential to produce viable seed in as little as 6-8 weeks (Bassett and Crompton, 1978; Miyanishi and Cavers, 1980; Weaver and McWilliams, 1980). While not measured directly, hard seed from *Chenopodium album* was observed at the MN site, which was also the site with higher overall C:N, suggesting that plants matured more quickly in the sandy, low OM soil, perhaps due to water stress (Turner, 1986). Low weed suppression capability in this project may have been a result of cover crop seeding rate and germination, as well as the high weed seed bank at both organic farms. Weed biomass was higher in our study than in comparable studies of similar species (Creamer and Baldwin, 2000). Nevertheless, the relationship between total biomass accumulation and weeds provides important indication of what level of weed suppression is likely to be achieved by summer cover crops.

Given the condensed growth timeline for these cover crops, it is likely that many if not most of the weeds were unable to set seed. This raises the question of whether weed suppression in short duration cover cropping is a benefit, or whether weed growth without opportunity for maturation would be an opportunity to reduce the weed seed bank. However, the inverse relationship between weeds and cover crop biomass proportionally indicates that weeds are a low productivity option to serve as a cover crop, though they may be a viable option for biomass accumulation in some circumstances (Wortman, 2016). Additionally, the risk of even a single plant going to seed can be significant; weed seed production from *Amaranthus* species in the presence of poor-competing cover crops can top 100,000 seeds m^{-1} (Brainard et al., 2011), and a single *Chenopodium* plant can produce over 70,000 seeds (Bassett and Crompton, 1978).

Cover crop maturity stage has important effects on biomass N mineralization and immobilization rates after termination. In our study, broccoli yield decreased in all cover crop treatments, suggesting that nutrients were immobilized by the cover crops and thus became unavailable for cash crop uptake. Cover crop C:N at termination determines the availability of cover crop nutrients to microbes, and thus affect the ecosystem services related to N retention and fertility (Finney et al., 2016). While some evidence suggests that C:N of 24:1 is ideal for microbial processing and nutrient release without immobilization (O'Connell et al., 2015b), others have found that organic soil amendments with C:N as low as 10 can cause immobilization (De Rosa et al., 2016). Biomass C:N in the current study was reliably below 24:1 in WI, but mineral N remained significantly lower in cover cropped treatments compared to bare control at broccoli transplant, which occurred one week after cover crop termination and incorporation (Wauters, 2020). The decreased N levels indicate nutrient immobilization, which may have contributed to decreased broccoli yield. Furthermore, yield was generally lower in LD treatment, especially at MN; in Y2, C:N in the LD treatment reached over 40, well above an ideal range for microbial mineralization. Mineral and organic N in soil at peak growth and early decomposition time points were lower in the cover crop treatment than in the bare treatments (Wauters, 2020), indicating that the living and decomposing biomass both led to decreased N availability for broccoli. Despite high soil moisture and temperature, decomposition processes did not release nutrients for the fall cash crop in time to avoid a yield penalty. The suggested window between cover crop termination and cash crop planting varies from two to three weeks (Clark, 2013), though others have found that N release can take place over multiple weeks and even months (Parr et al., 2014). In this study, the time between cover crop termination and cash crop planting was only one week, to improve the probability that the broccoli would mature before first frost and thus be able to withstand some freezing temperatures. Given the reduction in yield, one week appears to be insufficient. Additionally, the broccoli only reached maturity and was able to form heads in one of two years before persistent low temperatures arrested growth, indicating that both a spring and fall cash crop on either side of the cover crop is not feasible.

Conclusion

Summer cover crop use in northern climates could be a useful tool for vegetable growers seeking to protect and improve soil within complex rotations, especially in the northern climates experiencing an increase of extreme summer rain events that could erode bare soil. However, weed pressure and cash crop yield decreases remain significant barriers to adoption. In the MN soil, which had very low OM, yield decreases between cover cropped and bare unfertilized treatments indicates that fall cash crop planting is not financially feasible. In the higher OM soils in WI, the broccoli yield decrease was less dramatic; it would be worthwhile to quantify the cost of the tradeoffs between yield and the ecosystem services provided by the cover crop. Weed pressure can be reduced by summer cover crops, but not eliminated. These cover crops show potential for farmers, but care must be taken to integrate them into the system with enough time to reach maturity and decompose without impinging on cash crop growth. Demonstrating the benefits and limitations of cover crops as a diversification tool to enhance ecosystem services and resilience provides farmers with a clearer picture of how summer cover crops could be used in their operation, to respond to the multi-layered demands of food production and environmental stewardship to which farmers must continuously adapt.

Acknowledgments

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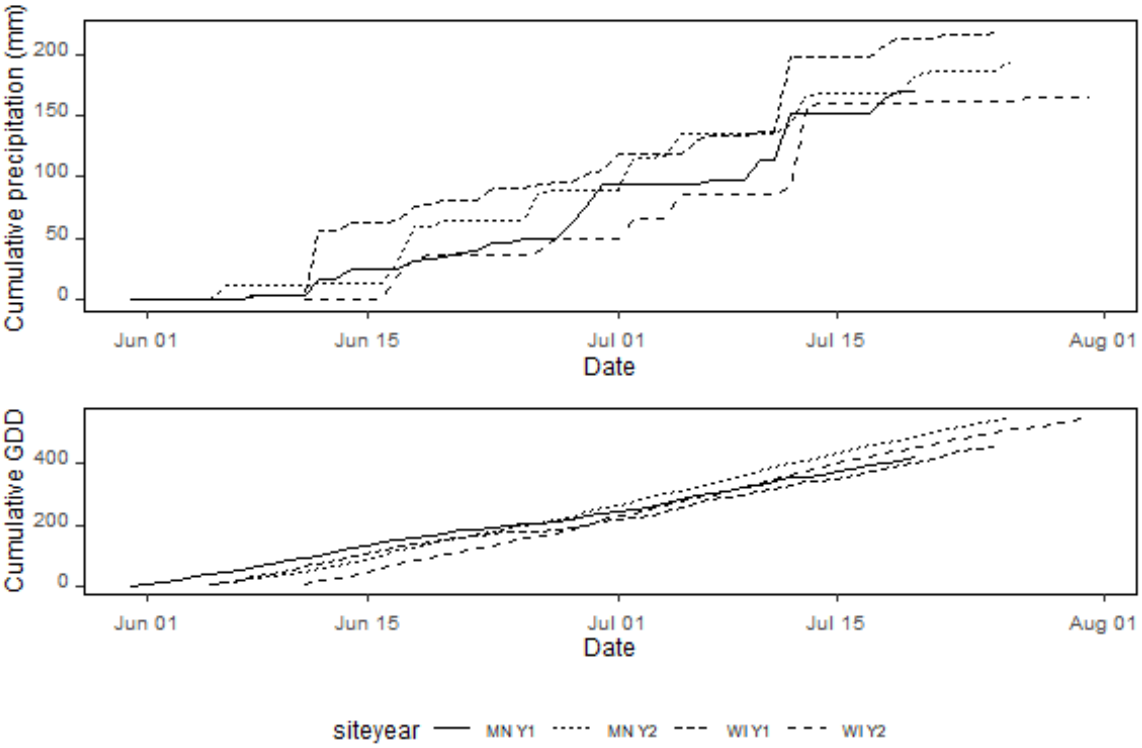

Figure 2.1. Cumulative precipitation (mm) and GDD (base temperature 10 C) for each site year during cover crop growth.

Table 2.1. Field management schedule for Y1 and Y2 field operations.

Field Operation	MN Y1	MN Y2	WI Y1	WI Y2
Long duration CC planting & Baseline soil sample	31-May	5-Jun	5-Jun	11-Jun
Irrigation	5-Jun	NA	NA	NA
Short duration CC planting	20-Jun	25-Jun	24-Jun	1-Jul
CC biomass sample & Termination soil sample	20-Jul	26-Jul	25-Jul	31-Jul
Broccoli transplant & Transplant soil sample	27-Jul	2-Aug	2-Aug	7-Aug
Broccoli fertilization	1-Aug	10-Aug	9-Aug	15-Aug
Broccoli harvest	5-Oct	NA	8-Oct	NA
Broccoli harvest	11-Oct	NA	13-Oct	NA
Broccoli harvest	20-Oct	NA	18-Oct	NA
Broccoli harvest	26-Oct	NA	29-Oct	NA
Broccoli biomass sample	NA	18-Nov	NA	10-Nov

Table 2.2. Total cover biomass, total biomass N, and weed biomass for all four sites years, separated by duration and species treatment.[1]

			MN			WI		
			total biomass	weed biomass	total biomass N	total biomass	weed biomass	total biomass N
year	duration	species	kg ha^{-1}					
Y1	SD	buckwheat	2320 a	709	55 a	3290 ab	505 b	114
Y1	SD	vetch & sudax	1570 b	1420	46.7 ab	3110 ab	1580 ab	121
Y1	SD	cowpea & sudax	1020 c	867	30.6 b	3550 a	2330 a	129
Y1	SD	sunn hemp	971 c	820	32.8 b	2220 b	1970 ab	95.1
Y1	LD	buckwheat	3170 a	398 b	47.5	7320 a	362 c	180 a
Y1	LD	vetch & sudax	2320 ab	1510 a	41.8	6930 ab	2060 b	161 ab
Y1	LD	cowpea & sudax	1990 b	1410 a	36.5	5400 bc	3020 ab	122 bc
Y1	LD	sunn hemp	1770 b	1730 a	33.9	4470 c	4370 a	112 c
Y2	SD	buckwheat	1790	1020	33.7	3760	530	140
Y2	SD	vetch & sudax	947	739	21.7	3730	2090	138
Y2	SD	cowpea & sudax	1810	1600	27.1	3160	751	116
Y2	SD	sunn hemp	1290	1260	25.2	2100	1600	86.3
Y2	LD	buckwheat	4910	1540 b	59.4 a	8540	1490 c	202 ab
Y2	LD	vetch & sudax	3750	2880 ab	43.1 ab	10400	3730 b	236 a
Y2	LD	cowpea & sudax	4040	2470 ab	46.3 ab	6380	3250 bc	128 b
Y2	LD	sunn hemp	3860	3840 a	35.0 b	8270	8260 a	198 ab

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[1] Lowercase letters indicate significant differences among the four species treatments within a duration treatment for a single site year. All means are estimated marginal means, to account for data. Mean separation via Tukey's HSD ($p<0.05$).

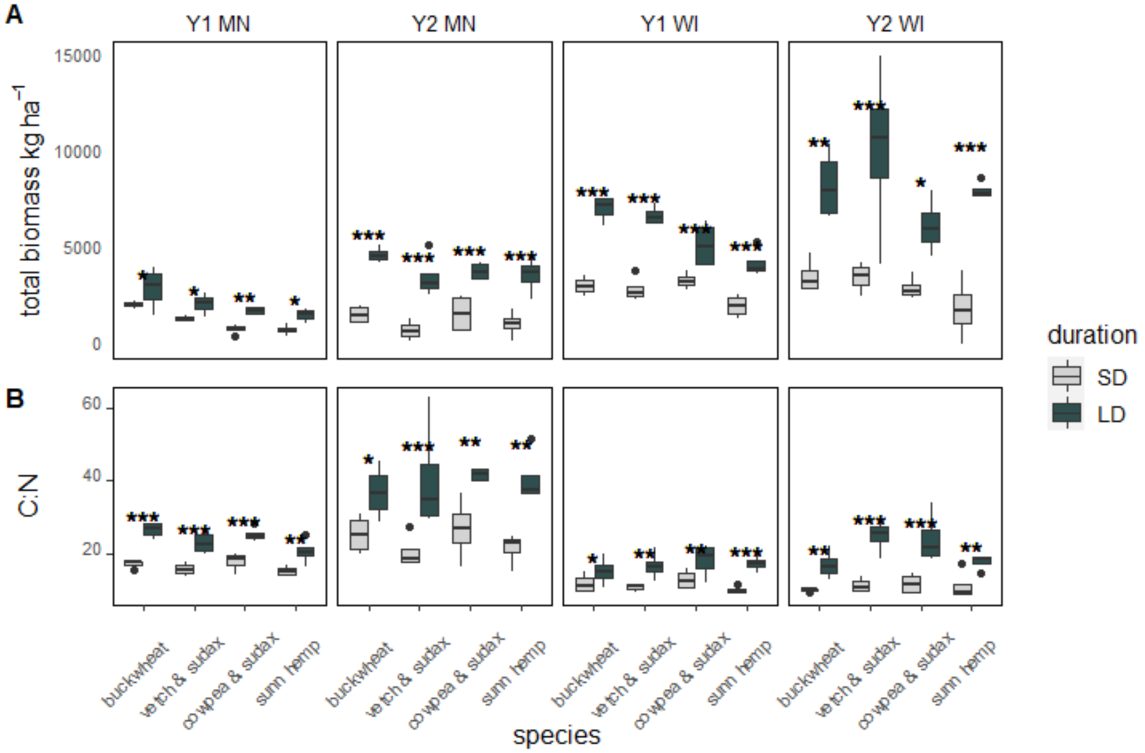

Figure 2.2. Total biomass and biomass N from each site year divided by species, compared between durations.[2]

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[2] Short duration (SD) appear on the left of each pair (lighter shading), long duration (LD) on the right (darker shading). Significant differences between duration for a species are indicated by stars above the pair. * p<0.05, ** p< 0.01, *** p<0.001.

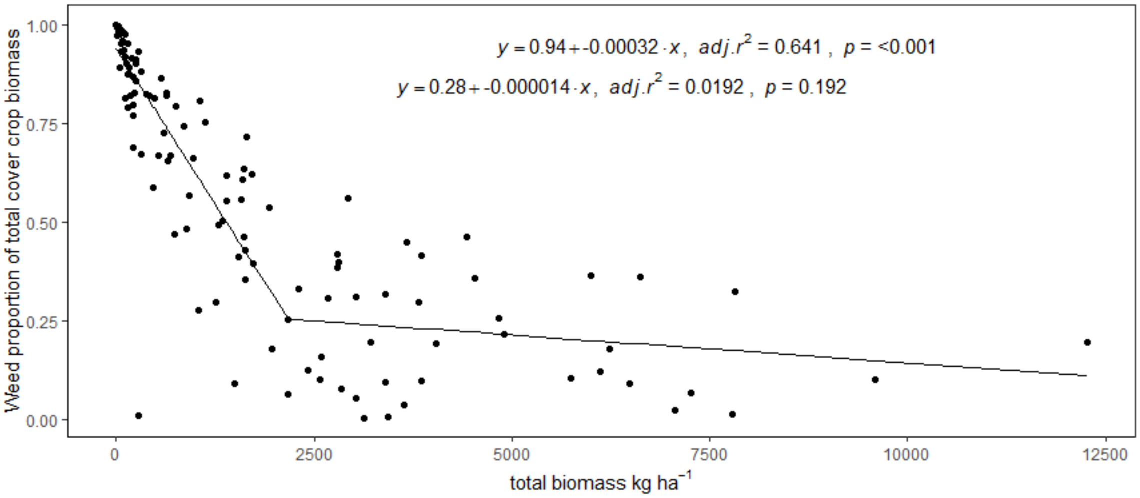

Figure 2.3. Relationship between total biomass and percentage of biomass from weeds.[3]

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[3] Best fit model chosen from linear, quadratic, and linear plus plateau, with equations for each of the two lines (top equation represents the line >2169 kg ha^{-1}, the bottom equation represents the line from 0-2169 kg ha^{-1}.

Table 2.3. Fall cash crop yield in Y1 by location for each species, averaged over duration in the absence of interaction effects.[4]

Species treatment	MN yield	WI yield
	--------------kg ha^{-1}---------------	
bare fertilized control	7181 a	11832 a
bare control	3429 b	10987 ab
vetch & sudax	2635 b	7746 b
sunn hemp	2531 b	8649 ab
buckwheat	2033 b	8731 ab
cowpea & sudax	1738 b	8376 ab

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[4] Crop yield calculated via estimated marginal means (EMMs). Lower case letters indicate mean separation via Tukey's HSD, $p<0.05$. Standard error (SE) for MN was 423 kg ha^{-1}, and for WI, 1380 kg ha^{-1}.

CHAPTER 3. SHORT-TERM WARM SEASON COVER CROPS FAVOR NUTRIENT RETENTION IN NORTHERN CLIMATES

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Summary

Cover crops diversify farming systems and can help promote improved nutrient cycling via recoupling of carbon (C) and nitrogen (N) cycles. Cover crops grown during short warm season fallows could prevent N leaching and build soil organic matter (SOM), or provide fertility to subsequent cash crops. However, little is known about services provided during short growing seasons in northern climates. To better understand the effects of cover crops on soil nutrient pools in specific edaphic conditions, we studied two contrasting soil types: one from Minnesota (low SOM, 11 g kg^{-1}) and one from Wisconsin (SOM 23 g kg^{-1}). Soils were collected and analyzed at two time points: 1) peak cover crop growth immediately prior to termination, and 2) early decomposition, one week after cover crop termination. Cover crop treatments were grown for short (30 d) and long (50 d) durations and were compared with mechanically weeded bare fallows. Soils were analyzed for extractable organic (EON) and mineral N (MinN), potentially mineralizable N (PMN), permanganate oxidizable C (POX-C), extractable organic C (EOC), and fluorescein diacetate hydrolysis (FDA). Living and decomposing cover

decreased MinN and EON compared to a bare control in both soils. However, FDA levels and soil C (POX-C and EOC) were unaffected due to cover crop or fallow treatments. Correlation analysis of all soil variables, biomass quantity, and C:N was compared with a partial correlation that controlled for cover crop biomass and C:N. The comparison showed significant (*Δ*R >0.25) impacts of cover crops on the relationship between MinN-PMN and MinN-EOC in the low OM site, with no changes in the higher OM site. The results of this research showed that even small amounts of biomass with varying quality can impact nutrient dynamics in low OM soils. We also observed that soil SOM content likely buffers against these effects in the soil containing 23 g kg^{-1}.

Introduction

Replacing bare fallows with cover crops diversifies farming systems and can help promote microbially-mediated nutrient cycling and a recoupling of carbon (C) and nitrogen (N) cycles (Drinkwater and Snapp, 2007). This recoupling can limit N leaching via plant uptake and contribute to soil fertility and SOM (Tonitto et al., 2006; Schipanski et al., 2014). In particular, warm season cover crops have demonstrated the capacity to accumulate high levels of biomass that physically protects soil and contributes to SOM and soil fertility during decomposition (Creamer and Baldwin, 2000; O’Connell et al., 2015b). In northern climates (Plant Hardiness Zones 1-4), warm season fallow periods are often less than two months in length and occur between spring and fall cash crop production, restricting the use of warm season cover crops. Such cover crops may be particularly useful in horticultural systems, where short-term opportunities for cover crop inclusion are more prevalent due to the varied nature of vegetable cash crop planting and harvest dates in spring, summer, and fall seasons. Summer fallow periods in northern zones often co-occur with high precipitation and thus increased N leaching risk. However, the N retention capability of warm season cover crops has not been established.

Ecosystem services such as N retention and biomass production, are well understood in winter cover crop systems and often have an inverse relationship to N supply and cash crop production, whereas soil C may increase or decrease independent of other services (Finney et al., 2017). Improved understanding of trade-offs between cover crop productivity and short-term N retention and supply of warm season cover crops offers new information about C and N cycling in cooler regions of the U.S. where cover crop use is gaining traction. As well, since soil C content is a known driver of N cycling dynamics (McGill and Cole, 1981; Drinkwater et al., 1996), additional knowledge clarifying the effect of relationships between C and N in these contexts will allow for cover cropping system performance improvements in a range of farm environments.

Cover crops can have meaningful and distinct effects on multiple soil N pools, all which can affect soil fertility for cash crop growth. Mineral N is of particular concern because of its high susceptibility for leaching and subsequent pollution of waterways. Nutrient uptake by living cover crops decreases mineral N. Comparisons of overwintered bare and cover cropped soil have shown that N uptake by living roots can decrease nitrate leaching losses by up to 94%, especially in high precipitation years (Kaspar and Singer, 2011; Hanrahan et al., 2018; Van Eerd, 2018). The magnitude of N retention from plant uptake depends on species; grasses retain the most leachable N, while weed species, given their genetic diversity, may be as effective as legumes at N retention (Wortman, 2016).

The effect of decomposing cover crops on mineral N are dependent on microbially mediated processes of immobilization and mineralization, which in turn depend on cover crop quantity and quality. Cover crop characteristics such as C:N of decomposing biomass drive the balance between mineralization (N fertility) and immobilization (N retention) (Drinkwater and Snapp, 2007; Liebman et al., 2018). Generally, cover crops contribute more to N retention than to N fertility, and this effect increases as biomass C:N increases (Finney et al., 2017). However, the magnitude of cover crop effects on N mineralization and immobilization, driven by residue type and C:N differences, varies greatly from quite large to undetectable (Zhou et al., 2012; Parr et al., 2014).

Because mineral N can be transient in soil, the effects of cover crops on N cycling may be better understood through quantification of additional N pools. Potentially mineralizable N (PMN) (Drinkwater et al., 1996) uses short- or long-term incubations after which mineral N is measured to quantify a theoretically available pool of non-mineral soil N. Meta-analysis shows that PMN correlates well with in-field mineralization (Reussi Calvo et al., 2018), indicating that it could have value as a measurement of soil fertility. In the presence of living roots, priming effects would lead to PMN increases (Drinkwater et al., 1996). After cover crop termination, PMN concentration depends on whether the microbial processing of residue results in net immobilization or mineralization. However, methodological diversity limits interpretation and predictive power of the measurement (Wang et al., 2003).

In addition to mineral N and PMN, short-term changes in organic N can also predict nutrient availability in soil. Organic N, measured as extractable organic N (EON), soluble organic N (SON), also called dissolved organic N (DON), has been shown via meta-analysis to correlate positively with soil mineral N concentrations (Ros et al., 2011), though without any evidence of a causal relationship. Like mineral N, EON is available for direct plant uptake and could be reduced by the presence of living cover (Murphy et al., 2000; Li et al., 2014). DON has been proposed as an underestimated loss pathway for N via leaching, so reduction via plant uptake could be an important ecosystem service of cover crops (Kessel et al., 2009). However, much is still unknown about the relationship of EON to other N pools (Ros et al., 2011). Some suggest that EON is not affected by short-term C and N inputs nor N uptake, but represents a stable, internally-cycled pool of soil N (Quan et al., 2018). If EON is part of a stable soil-internal N pool, it may not be responsive to cover crops during growth nor decomposition.

While the long-term effects of cover crops contributing to SOM are well-established, the short-term effects of living and decomposing cover crops on labile SOM are variable. Cover cropping increases SOM compared with bare soil (Ding et al., 2006), but in the short term, rhizodeposits from living roots could lead to increased C mineralization (Zhu et al., 2014). Mineralization of labile C can, in turn, lead to N mineralization, counteracting the N retention benefits for which cover crops are known (Kuzyakov et al., 2000). Labile carbon pools such as particulate organic matter (POM) and POX-C have demonstrated response to cover cropping (Butler et al., 2016; Jilling et al., 2020), but POX-C has been shown to be more sensitive to tillage than cover crops (Hurisso et al., 2016). This may be particularly true for low OM soils, in which tillage can stimulate rapid accumulation of labile C pools by stimulating microbial activity (Williams et al., 2017). Measurement of multiple C and N pools during growth and during decomposition is necessary to understand how cover crops affect soil C and N pools in the short-term, and thus clarify when to expect tradeoffs between nutrient retention and supply. In particular, measuring the impact of soil nutrient pools on one another, and when cover crops change those relationships may provide mechanistic insights on the impacts of cover crops on short-term nutrient cycling.

The objectives of this study were to: 1) Determine the effect of warm season cover crops on short-term indicators of soil N and C cycling; 2) Quantify changes in soil N and C at key points of cover crop management (peak growth and early decomposition), and 3) Elucidate relationships between soil nutrient pools affected by cover crop biomass quantity and quality. To further tease apart the effects of specific edaphic conditions on these pools, we conducted the study in two contrasting soil types in similar northern regions in Minnesota and Wisconsin. We predicted that the cover crops would decrease mineral N at PG, but increase mineral N during decomposition, and that soil C would not be affected by the living cover crops. Furthermore, we predicted that increases in soil C during decomposition would be influenced by soil N.

Materials and Methods

The experiment was conducted in the summers of 2017 (Y1) and 2018 (Y2) on distinct plots on two certified organic working vegetable farms in Minnesota (MN) and Wisconsin (WI), both in Plant Hardiness Zone 4A. The MN site was a Braham loamy fine sand, measured SOM 11 g kg^{-1}. The WI site was a Crystal Lake silt loam, measured SOM 23 g kg^{-1}. Cumulative GDD (with baseline 10 C) for the MN site were 416.9 and 545.9 in Y1 and Y2 respectively, and for the WI site, 450.6 and 549.1. Site management was based on farmer equipment and best management practices for each location (Table 3.1).

Experimental design and treatments

Each site year used a randomized complete block experimental design with four replicates. Each block consisted of a factorial design of four cover crop treatments and two duration treatments. Cover crop treatments included two monocultures and two bicultures; monocultures included buckwheat (*Fagopyrum esculentum*) (75 kg ha^{-1}) and sunn hemp (*Crotalaria juncea*) (38 kg ha^{-1}) and biculture included chickling vetch (*Lathyrus sativus*) (75 kg ha^{-1}) and sorghum-sudangrass (sudax) (*Sorghum bicolor x S. bicolor var. Sudanese*) (42.6 kg ha^{-1}), and cowpea (*Vigna unguiculata*) (44.8 kg ha^{-1}) and sudax (42.6 kg ha^{-1}). All four treatments were planted for two durations (the time the cover crop was in the ground), short and long duration, to represent realistic available planting windows in a northern vegetable rotation. Each replicate included two bare controls (one for each duration treatment). The long duration planting was seeded in early June following spring arugula harvest. The short duration planting was seeded three weeks later. All cover crops were left unweeded throughout growth. Weeds were removed weekly from bare controls. Long and short duration cover crops were terminated mechanically on the same date, 50 days after planting (DAP) the long duration treatments and 30 DAP the short duration treatments. Two days after termination, all treatments and bare controls were tilled to incorporate residue. Cover crop and weed biomass production and subsequent fall cash crop production yield are discussed in (Wauters, 2020).

Soil analysis

Volumetric water content (VWC) and temperature (in C) were measured continuously during cover crops growth using Decagon 5TM probes placed 15 cm below the soil surface. Sensors were only used at MN in Y1 due to equipment limitations. Two sensors were placed in three of four replicates of the long duration cover crop treatments. In Y2, sensors were placed in two of four replicates at MN and WI, in the long duration bare and vetch & sudax treatment. Sensor irregularities and low replication precluded statistical inference.

Soils were sampled at cover crop peak growth (PG), immediately before termination, and 5 days after incorporation during early cover crop decomposition (ED), when fall broccoli was transplanted into the field. A composite sample of ten cores from the top 15 cm were collected and homogenized in a bucket then split into fresh and dry subsamples. Fresh samples were sieved to 2 mm and stored in an airtight container at 4 C and analyzed within 7 days. Dry subsamples were air-dried at 30 C for at least 72 hours before grinding and sieving them to 2 mm before storing in airtight containers until analysis. Samples were analyzed for mineral N, PMN, organic N, POX-C, extractable organic C, as well as fluorescein diacetate hydrolysis (FDA) as a proxy for microbial activity to contextualize the other measurements.

Soil N content was determined on fresh samples for baseline extractable nitrate-N (NO_3-N), ammonium-N (NH_4-N), organic N (EON) and after a 7-day anaerobic incubation for potentially mineralizable N (PMN) (Moebius-Clune et al., 2016). Fresh and incubated soils were shaken for 1 hr in 1 M KCl, after which nitrogen was extracted from the soil solution via gravimetric filtration, and then frozen at -20 C for analysis.

Mineral N (MinN), the sum of NO_3-N + NH_4-N for baseline and PMN samples was quantified via colorimetric measurement of NH_4-N and NO_3-N/NO_2-N (Hood-Nowotny et al., 2010). Baseline NH_4-N was near 0 for all treatments, and is not reported directly, but was used for calculation of PMN and extractable organic N (EON). PMN is reported as the net NH_4-N after the anaerobic incubation. The calculation of EON followed the measurement of total extractable N (TEN), which was quantified via high temperature catalytic oxidation of all N compounds to NO using a TOC-CPH analyzer with a TNM-1 module and ASI-V autosampler (Shimadzu Scientific Instruments, Columbia, MD). We calculate EON as TEN - (NH_4-N + NO_3-N) for each sample (Jones and Willett, 2006; Hood-Nowotny et al., 2010). Some methods use the terms TDN (total dissolved N) and DON (dissolved organic N) instead of TEN and EON; we define DON as the N recoverable from the soil solution in situ, while EON is DON + additional organic compounds that enter solution during the extraction process, following Ros et al. (2009). Extractable organic carbon was determined from the soil extracts as EON. Soil extracts were purged of CO_2 and then calculated via catalytic oxidation of NPOC to CO_2 using a TOC-CPH analyzer and ASI-V autosampler (Shimadzu Scientific Instruments, Columbia, MD).

Fluorescein diacetate levels were determined following a modification of Adam and Duncan (2001) and Green et al. (2006). For each sample, a pair of tubes with 1 g air-dried soil was filled with 7.5 mL 60 nM potassium sulfate buffer, and then one pair of samples (“control”) received 5 mL of a 2:1 chloroform:methanol solution, while 0.1 g 1000 mg/L fluorescein diacetate (FDA) was added to the other pair (“reacted”). All samples were incubated for 1 hour at 37 C, after which the chloroform:methanol solution was added to the control samples, and the FDA was added to the reacted samples. Samples were then centrifuged for 5 min at 3000 rpm, after which the supernatant was extracted and read for absorbance values at 490 nm on a spectrophotometer. Enzyme concentration was calculated as the absorbance of the control samples subtracted from the reacted samples. Standard dilutions of fluorescein sodium salt were used to generate a standard curve.

Permanganate oxidizable carbon (POX-C) was measured according to Weil et al. (2003). Briefly, 2.5 g of air-dry soil was reacted with a 0.2 M KMnO4 solution, which is a strong oxidizer. Diluted supernatant from each sample was transferred to 96-well plates and measured for absorbance at 540 nm on a spectrophotometer. Absorbance was fitted to a standard curve from manually diluted KMnO4, and calculated to determine C oxidation by KMnO4 reaction.

Statistical analysis

To test the effects of living cover and decomposing residue on each soil N, C, and FDA activity, linear mixed effects models were fitted for each time point with site year, species treatment, and duration treatment averaged across blocks as predictor variables. Each of the four site years were analyzed separately due to interaction between species and duration for MinN, PMN, and EON. In each model, block was a random effect, and species and duration treatment were fixed effects. Dunnett's tests were conducted to compare the estimated marginal means of bare control to each cover crop treatment at each time point for each soil measurement. For POX-C, EOC, and FDA, in the absence of differences between the bare control and cover crop treatments, models compared the estimated marginal means at a specific time point, with block as a random effect.

In addition to modeling the effects of cover crops on individual soil parameters, we used Pearson correlations to assess pairwise relationships between all soil parameters at ED, divided by location. Given that cover crop inputs are known to affect soil parameters, we also conducted partial correlations controlling for recently incorporated cover crop biomass (cover crop quantity) and C:N (cover crop quality) to see if this changed relationships between soil variables. We used a threshold value of (ΔR > 0.25) between pairwise correlations and partial correlations (Birkhofer et al., 2018) to indicate which soil variables were most affected by cover crop biomass quantity and quality. Statistical analysis was carried out using R version 3.6.1, using *lme4* and *multcomp* for mixed model analysis, and *ggplot2* for visuals (Hothorn et al., 2008; R Core Team, 2013; Bates et al., 2015; Wickham, 2016). The correlations were analyzed using *corx* and *corrr* (Conigrave, 2019; Kuhn et al., 2020).

Results

Soil N pools

The presence of living and decaying cover crops affected soil N concentrations in multiple pools, with further differences due to duration of time cover crops were grown. In the long duration treatment (50d), MinN was higher in the bare control than the cover cropped treatments for all species mixtures in all four site years at PG and ED (

Figure 3.1). The magnitude of difference between the bare control and the species treatments was greatest in WI at PG, which was over 10 times higher in Y1 and 13 times higher in Y2. In MN, bare plots were between 120-180% higher in the control than the treatment plots. EON followed similar patterns to MinN. The greatest differences occurred in WI at PG where the control treatment was 3.6 and 4.6 times higher than the cover cropped treatments Y1 and Y2, respectively. The long duration treatments showed few differences in PMN between the bare control and cover cropped treatments at PG and ED, apart from Y2 WI, in which all cover crop treatments had higher PMN than the control.

The short duration treatments (30d) had similar patterns of MinN, EON, and PMN concentrations to the long duration treatments for both years in WI. Low concentration of MinN in Y1 led to the greatest difference in WI, in which the bare control was 8 times higher than the cover crop treatments. There were no differences in MinN, EON, and PMN between the control and cover crop treatments in either year at MN (Figure 3.2). In WI, similar to the long duration treatment, all four cover crops had lower MinN and EON than the control at PG, and all except for buckwheat and vetch & sudax continued to be lower at the ED time point, one week after termination. The PMN in short duration also showed similar patterns to the long duration at both locations. In Y1 MN, the vetch & sudax and sunn hemp treatments both had higher PMN than the bare control tat decomposition. In Y2 WI, PMN was higher in the cover crop treatments than the bare control for cowpea & sudax and sunn hemp at PG, and for cowpea & sudax, sunn hemp, and vetch & sudax at ED. There were no differences in PMN concentration between control and cover crops in Y2 MN or Y1 WI.

Carbon and microbial cycling

Living roots and decaying residue from warm season cover crops did not affect short-term labile carbon and microbial activity including EOC, POX-C, and FDA with three exceptions across the four site years, two for EOC and one for FDA (Table 3.6). Mean concentrations of POX-C, EOC, and FDA were higher in WI than in MN ($P<0.05$), except for FDA at PG in Y2. Mean POX-C concentrations averaged across species and duration treatments in MN ranged from 180 mg kg^{-1} at PG in Y2 to 221 mg kg^{-1} at ED in Y1. In WI, POX-C concentrations were more than double that of MN, from 445 mg kg^{-1} at ED in Y1 to 520 mg kg^{-1} at ED in Y2. Mean EOC concentrations were also generally higher in WI than MN, ranging from 17.8 mg kg^{-1} at PG in Y1 to 26.8 mg kg^{-1} at PG in Y2, while concentrations at MN ranged from 7.03 mg kg^{-1} at PG in Y1 to 17.9 mg kg^{-1} at PG in Y2. Mean FDA was less distinct across locations, with no differences between MN and WI in Y1 at PG, in which the mean concentration across all treatments was 14.5 mg kg^{-1}.

Soil temperature and moisture

Soil temperature trended lower in the covered plots than in the bare control, and the differences increased over the course of cover crop growth (

Figure 3.3). Precipitation and GDD were relatively consistent across all four site years (Figure 3.4), and cover crops did not affect soil volumetric water content (data not shown).

Soil N concentration changes between PG and ED time points

In the one-week period between PG and ED, concentrations of MinN and EON in MN increased in both years in the treatment and control. In WI, MinN and EON in the control decreased (Figure 3.5), but increased between PG and ED in the cover crop treatments. The change in concentration between PG and ED of PMN, EOC, POX-C, and FDA also showed no consistent differences between the bare and covered treatments (Table 3.6).

Correlations among soil nutrient indices

Pearson correlations describe the strength of relationship between soil and biomass indices measured at PG and ED. Correlation coefficients range from 0-1 as the strength of the relationship increases, while the sign (+ or -) of the coefficient indicates whether the relationship was positive or negative. In MN, strong negative correlations were found between total biomass and Min N ($r=-0.47$, $p<0.05$), as well as total biomass and biomass C:N ($r = -0.51$, $p<0.05$). Total biomass C:N was also negatively correlated with EON (-0.29, $p<0.05$). These findings reflect the decreased N in the cover crop treatments compared with the bare control (Table 3.2). Total biomass had positive correlations with PMN and EOC, the two measurements of labile soil SOM, indicating contributions from biomass to these pools. PMN and EOC were also highly correlated, as were MinN and EON.

Partial correlations among the soil indices with total biomass and biomass C:N as control variables increased the R for two correlations that were not significant in the full correlation: MinN with PMN, and MinN with EOC (

Figure 3.6). Soil PMN and EOC remained highly correlated ($r = 0.54$, $p<0.05$) (Table 3.3).

In WI, the full correlation matrix exhibited fewer significant relationships between soil indices, though patterns were similar to MN (Table 3.4). Cover crop biomass was negatively correlated with MinN, and positively correlated with PMN and EOC, indicating that at both locations, decomposing biomass impacting labile SOM differently than MinN. The partial correlation matrix for WI did not have any *Δ*R >0.25, (Table 3.5), indicating that cover crop biomass and C:N did not impact the relationships between soil variables.

Discussion

This study sought to quantify the impact of short-term warm season cover crops on coupled C and N cycling at peak cover crop growth, and shortly after termination. Knowledge of the degree to which living roots and decomposing biomass affect specific N and labile C pools can guide cover crop use that will enhance specific ecosystem services. Increased cover crop management knowledge may improve farmers' ability to use cover crops to diversify their systems and maintain cash crop productivity. This study provides evidence that warm season cover crops affect N cycles, even when grown for as little as 30 days. Specifically, we found that the cover crops contributed to N retention, as measured via MinN and EON, both at PG and within the first week after termination when cover crop biomass was beginning the decomposition process. Cover crops also contributed to potential N fertility, as measured by PMN. However, continued low MinN and EON concentrations in cover cropped treatments at ED indicate that increases in cover crop treatment PMN did not lead to mineralization one week following biomass incorporation. These results are in contrast to winter cover crops, which have been associated with increased warm season cash crop yield (Zhou et al., 2012; Van Eerd, 2018, among others). Winter cover cropping can take advantage of longer decomposition periods that result in plant-available fertility over many weeks if not months or into the next growing season (Parr et al., 2011; Campiglia et al., 2014).

The MinN and EON decrease in cover cropped treatments compared to bare controls suggests that warm season cover crops can positively contribute to the ecosystem benefit of N retention. Limiting N leaching via cover crops could be important to counteract the negative effects of over-fertilization common in horticultural production due high premium on harvest quality. Historically, fertility management innovations in these systems have paid scant attention to environmental concerns (Mikkelsen and Bruulsema, 2005). Nutrient retention is a biomass-driven ecosystem service (Finney et al., 2016). Our biomass accumulation results (Wauters, 2020) confirm that total biomass was generally within normal range for warm season cover crops (O'Connell et al., 2015b), and above that of many winter cover crops (Kaspar and Bakker, 2015). Nitrate formed the vast majority of mineral N at both sampling time points. One factor that may have contributed to the N retention benefit of the cover crops is low proportion of legume biomass. Although three of the four species included legumes, their relative contribution to biomass was quite low (Wauters, 2020), such that a majority of the biomass consisted of cover crop and weedy grass and broadleaf species, demonstrated to be more effective than legumes at N retention (Tonitto et al., 2006; Finney et al., 2016; Wortman, 2016). However, the N retention benefits of summer cover crops may be lost if N is released during precipitation in fall and winter.

Our results provide evidence for nutrient immobilization immediately after termination of the cover crops. These data support findings showing legume cover crops' peak nutrient release to occur 10 weeks following cover crop termination (Parr et al., 2014). While at least one cover crop species enhanced potential soil fertility (PMN) relative to a bare control in three of four site years, that potential fertility was not translated to available soil N, as measured by the change in MinN and EON. Changes in MinN and EON concentrations between the two sampling time points indicated that soil fertility differences at the two sites affected the extent to which N pools responded to cover crop incorporation and tillage. In MN, tillage increased MinN and EON, while in WI, tillage only increased MinN and EON in the cover cropped treatments, but decreased in the bare control. Importantly, despite the decrease, MinN and EON were still higher in the bare control than in any of the cover cropped plots in WI, so the increases in the cover cropped treatment did not result in more available fertility than in the bare control.

In addition to finding lower MinN and EON at ED, fall cash crop yield (broccoli) in the cover cropped treatments was lower than that of the bare control (Wauters, 2020), indicating that long-term release of N from cover crops was also not realized by the time of broccoli harvest. These findings point to a significant potential tradeoff for warm season cover crop use, especially in low OM soils, where cover crop SOM additions may contribute ecosystem services to the short-term detriment of cash crop production. While biomass contributions could increase SOM and fertility in the long term, our data suggest that when lacking a significant proportion of legume biomass, warm season cover crops may be unsuitable to grow immediately before fall cash crops in absence of additional fertility sources. Whether additional fertility is economically viable depends on the dynamics of individual farms, but one option could be to pair manure applications with cover crops (Cambardella et al., 2010; Thilakarathna et al., 2015).

Consistent differences between the two sites demonstrate the importance of examining nutrient cycling in distinct edaphic conditions. The sites were chosen to reflect distinct but common soil types in the Upper Midwest within the same Plant Hardiness Zone (4A), with SOM concentrations acting as a proxy for inherent soil fertility. Bare controls at both sites had higher MinN and EON concentrations than the cover crop treatments. However, cover crop treatments at the higher OM site (WI) were more similar to concentrations at the lower OM site (MN) than they were to the bare control, highlighting cover crops' ability to reduce leachable N even during a short period of growth. The effectiveness of warm season cover crops at reducing leachable N could make them particularly useful as short-term nutrient scavengers during brief fallow periods in high-input environments such as high tunnel production (Montri and Biernbaum, 2009; Knewtson et al., 2010). However, this substantial capability to retain N must be taken into account when planting subsequent cash crops, which may suffer from nutrient deficiencies without additional fertilization.

The differences in correlation and partial correlation strengths among soil indices in MN and WI suggest the impacts of cover crop biomass on relationships between short-term nutrient pools alters based on soil quality (e.g., soil texture, SOM level). In a lower fertility sandy soil (MN), cover crop biomass and C:N was found to affect the relationship between soil nutrient pools. While no causal interpretation can be drawn from these data, it is clear that the presence of cover had dramatic effects in the low OM soils. The strong effect of total biomass and biomass C:N on the relationship between MinN and EOC and PMN indicates that decomposing cover crop residues increased immobilization of MinN, which had cascading effects on levels of other labile C and N pools. Mechanistic understanding of the relationships between soil indices as they are affected by cover crops would allow researchers and farmers to harness these dramatic effects to optimize cover crop use within specific farming systems.

Conclusion

Short-term cover crops can have meaningful and distinct effects on soil N pools, but not on labile C. While cover crops can provide the ecosystem service of reducing leachable N, the nutrient cycling processes influenced by short season cover crops do not result in readily available nutrients for plant uptake by the following cash crop. Decreasing leachable soil nitrate at the expense of cash crop yield indicates that warm season cover crops may not be a suitable precursor to fall cash crop production in rotations that necessitate a short period between cover crop termination and cash crop planting. However, warm season cover crops may be well-suited for soil protection and excess nutrient removal following spring cash crop production, also as a mechanism to increase diversity. Additionally, more studies that model the relationships between soil C and N pools, especially where legumes are included as a significant biomass contributor, can help guide future research on the interactions between cover crops and soil nutrient cycles more holistically, and lead to better management and use of cover crops in a variety of cropping system circumstances.

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Table 3.1 Field management schedule for Y1 and Y2 at MN and WI sites.

Field Operation	MN Y1	MN Y2	WI Y1	WI Y2
Long duration CC planting & Baseline soil sample	31-May	5-Jun	5-Jun	11-Jun
Irrigation	5-Jun	NA	NA	NA
Short duration CC planting	20-Jun	25-Jun	24-Jun	1-Jul
Peak growth soil sample (cover crop termination)	20-Jul	26-Jul	25-Jul	31-Jul
Early decomposition soil sample (broccoli transplant)	27-Jul	2-Aug	2-Aug	7-Aug

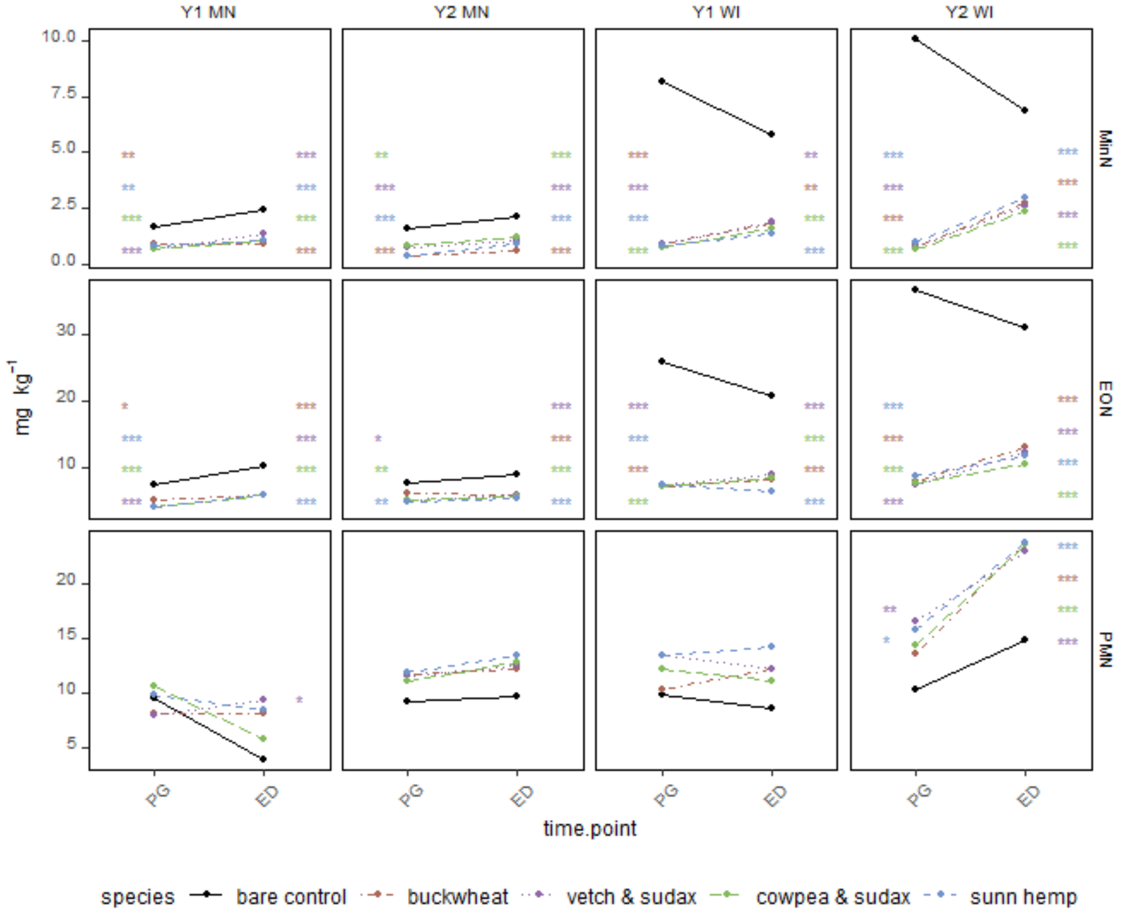

Figure 3.1 MinN, EON, and PMN measured in long duration treatment for all four site years.[5]

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[5] Stars indicate a significant difference (* p<0.05, ** p< 0.01, *** p<0.001) between the bare control (solid black) and the cover crop treatments (non-black, dashed and dotted lines) at a given time point.

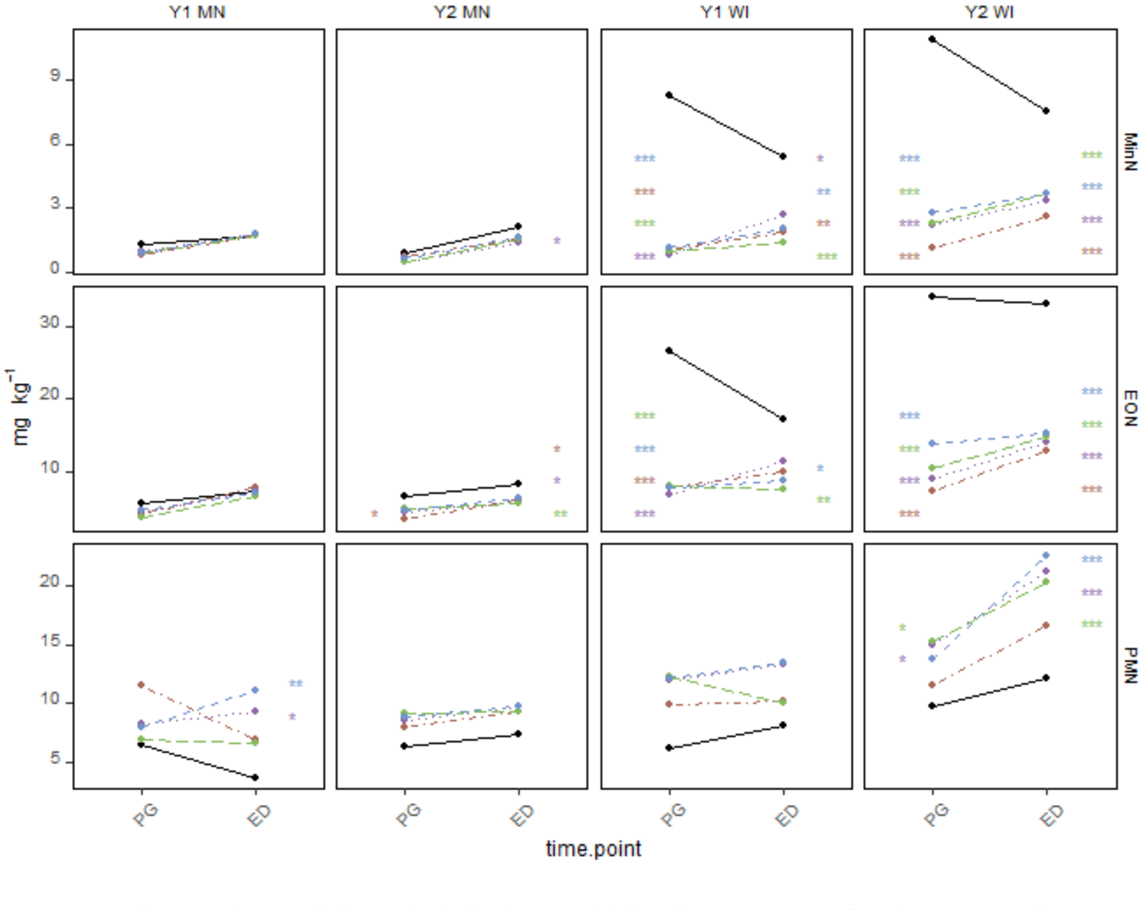

Figure 3.2 MinN, EON, and PMN measured in short duration treatment for all four site years.[6]

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[6] Stars indicate a significant difference (* $p<0.05$, ** $p< 0.01$, *** $p<0.001$) between the bare control (solid black) and the cover crop treatments (non-black, dashed and dotted lines) at a given time point.

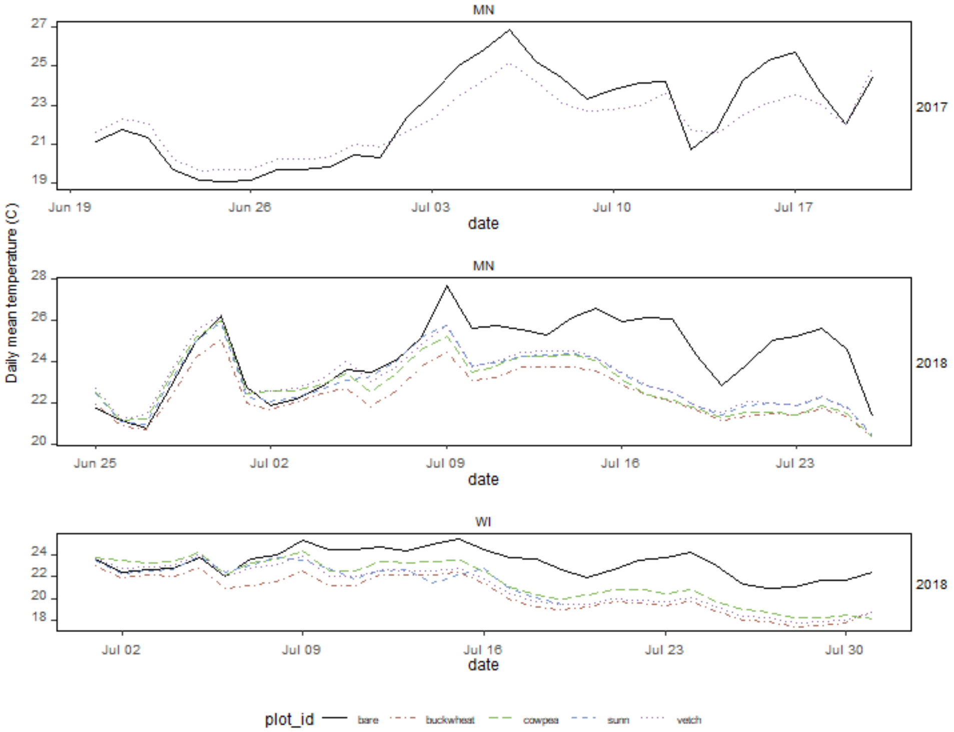

Figure 3.3 Soil temperature (C) for MN Y1 and Y2 and WI Y2 starting at cover crop seeding and ending at cover crop termination.[7]

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[7] Each line represents the soil temperature readings for a specific plot from 1 or 2 probes. Solid lines represent the bare control, non-solid colored lines represent cover crop treatments.

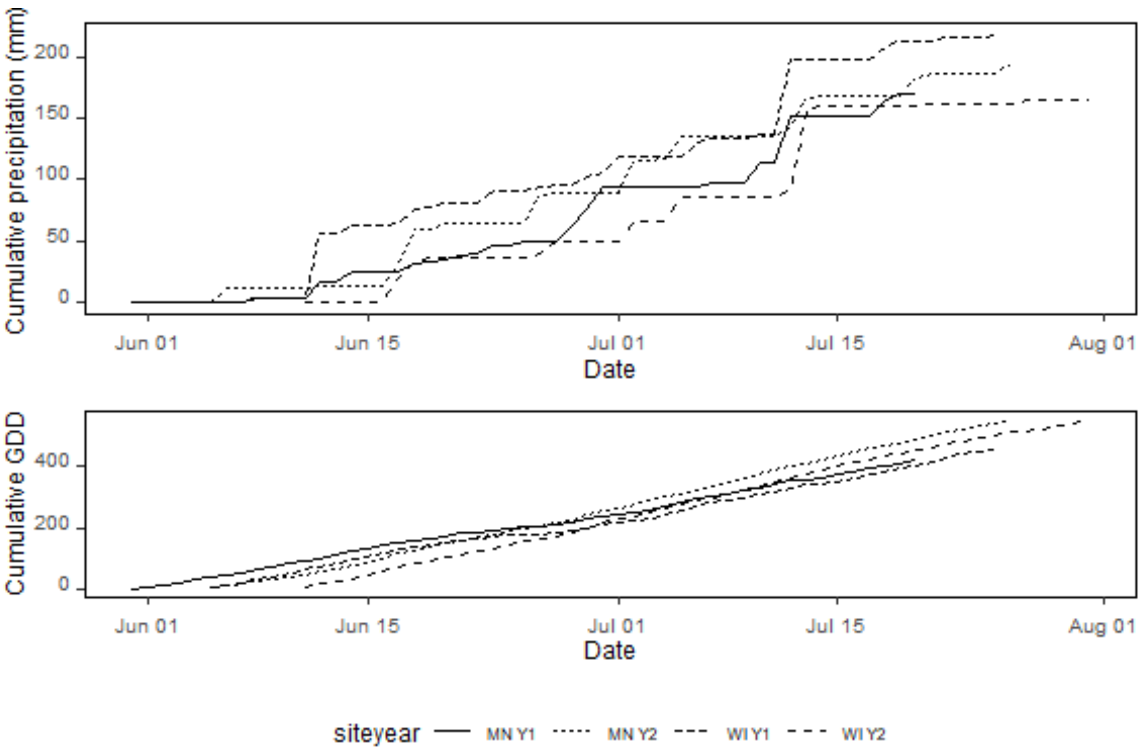

Figure 3.4 Cumulative precipitation and GDD for all four site years.[8]

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[8] GDD calculated from a base temperature of 10C, based on ideal growing conditions for the cover crop species included in the study. Precipitation data taken from closest NOAA weather station to each site, measured in mm per day.

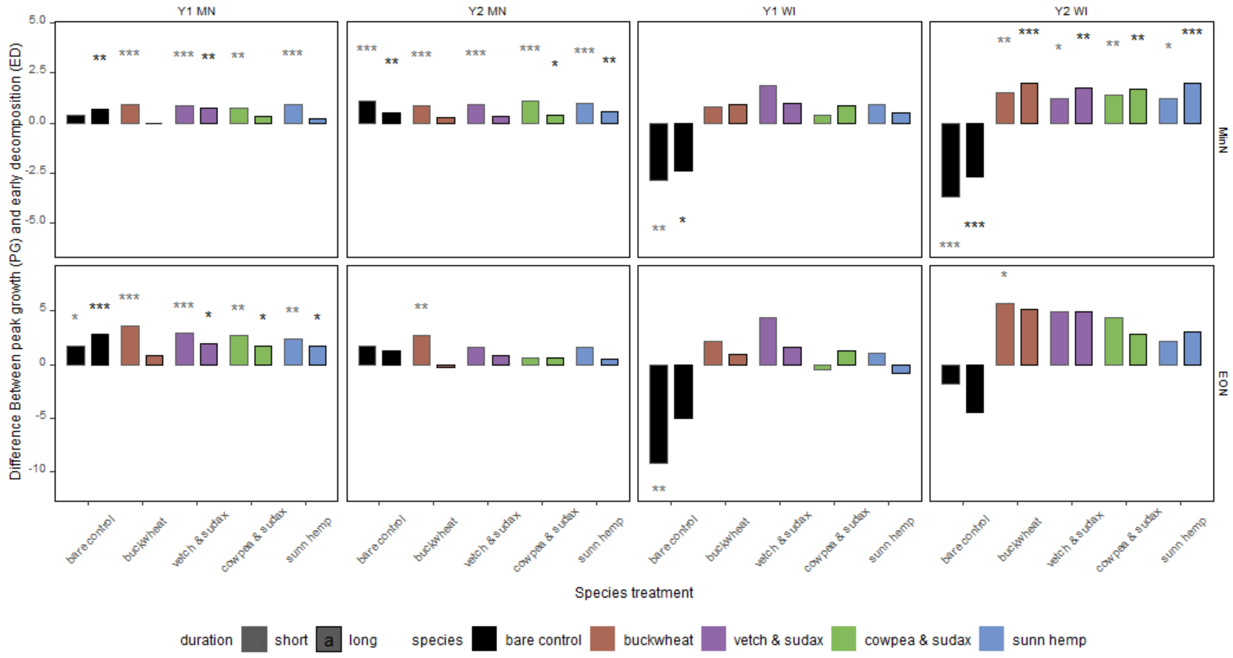

Figure 3.5 Degree and direction of change in MinN and EON concentration during one week between PG and ED sampling.[9]

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[9] Bars extending above the line indicate positive change. Bars extending below the lines indicate negative change. Colors indicate species treatment. The left bar in each pair is the long duration treatment mean; the right bar is short duration. Stars indicate significant differences between PG and ED within a given species and duration treatment within a site year (* $p<0.05$, ** $p< 0.01$, *** $p<0.001$).

Table 3.2 Full correlations at ED in MN between soil and biomass indices.[10]

	MinN	PMN	EON	EOC	POX-C	FDA	Biomass kg
PMN	0.07						
EON	0.53*	0.17					
EOC	0.01	0.65*	-0.01				
POX-C	0.29*	0.15	0.02	0.09			
FDA	0.24	0.31*	0.32*	0.33*	0.37*		
Biomass kg	-0.47*	0.37*	-0.11	0.51*	0.14	0.25*	
Biomass C:N	-0.51*	0.44*	-0.29*	0.58*	-0.17	0.06	0.78*

Table 3.3 Partial correlations at ED in MN between soil indices, controlling for biomass quantity and C:N.[11]

	MinN	PMN	EON	EOC	POX-C
PMN	.38*				
EON	.52*	.32*			
EOC	.46*	.54*	.19		
POX-C	.34*	.26*	-.13	.21	
FDA	.41*	.30*	.31*	.35*	.27*

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[10] Stars indicate significant correlation ($p<0.05$ = *).

[11] Stars indicate significant correlation ($p<0.05$ = *).

Table 3.4 Full correlations at ED in WI between soil and biomass indices.[12]

	MinN	PMN	EON	EOC	POX-C	FDA
PMN	0.48*					
EON	0.77*	0.45*				
EOC	0.30*	0.24	0.42*			
POX-C	0.34*	0.38*	0.39*	0.12		
FDA	0.07	-0.15	-0.16	0.13	-0.06	
Biomass kg	0.05	0.28*	0.06	0.27*	0.18	0.24
Biomass C:N	-0.29*	0.26*	-0.20	0.09	-0.11	0.11

Table 3.5 Partial correlations at ED in WI between soil indices, controlling for biomass quantity and C:N.[13]

	MinN	PMN	EON	EOC	POX-C
PMN	.59*				
EON	.75*	.52*			
EOC	.29*	.19	.42*		
POX-C	.27*	.40*	.34*	.04	
FDA	.05	-.23	-.19	.06	-.12

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[12] Stars indicate significant correlation (p<0.05 = *).

[13] Stars indicate significant correlation (p<0.05 = *).

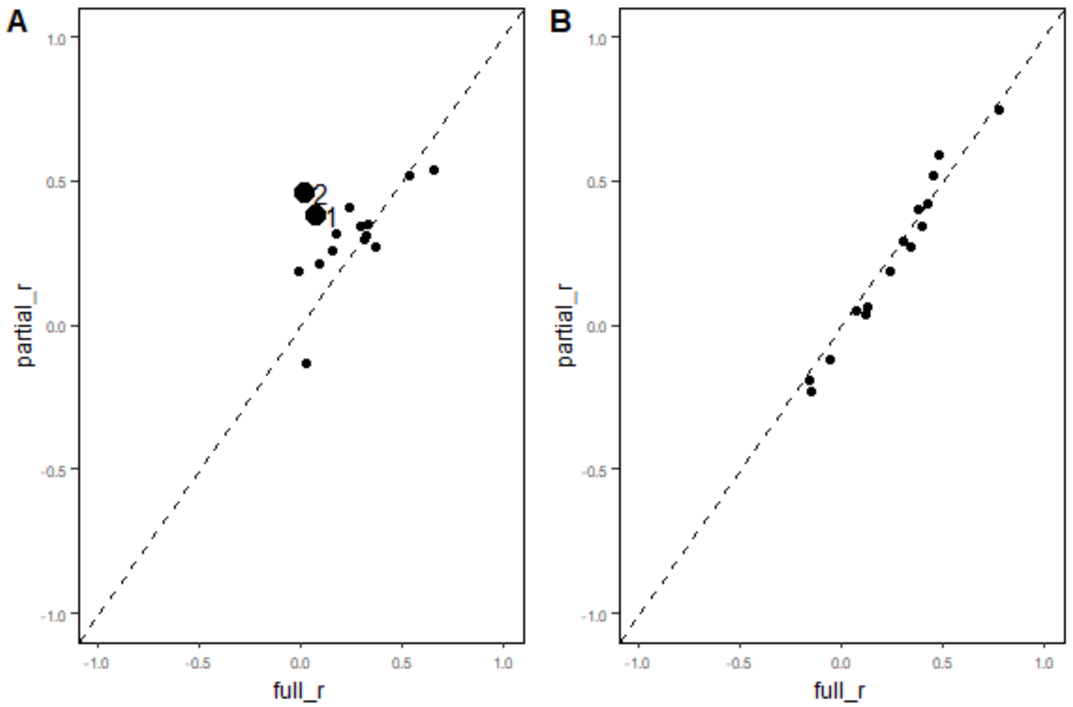

Figure 3.6 Relationship between standard and partial Pearson correlations for MN (A) and WI (B).[14]

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[14] Dash line represents 1:1 relationship between partial and full correlation coefficients. Normal Pearson correlations compared all six soil indices to one another, while the partial correlation controlled for total cover crop biomass and cover crop C:N. Two correlations had *Δ*R >0.25 and are numbered: 1 = MinN and PMN; 2 = MinN and EOC. Both 1 and 2 resulted in significant correlations.

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Table 3.6 EOC, POX-C, and FDA concentrations at PG and ED for all site years.[15]

			MN						WI					
			EOC		POX-C		FDA		EOC		POX-C		FDA	
			PG	ED	PG	ED	PG	ED	PG	ED	PG	ED	PG	ED
year	duration	species	mg kg $^{-1}$											
Y1	short	bare control	6.21	5.1	208.09	216.31	6.04	6.61	17.7	31.27	421.45	456.09	10.99	15.15
Y1	short	buckwheat	6.87	7.86	206.18	207.81	7.96	8.24	17.85	24.17	488.64	465.03	11.26	13.93
Y1	short	vetch & sudax	6.5	7.04	234.72	255.01	7.4	10.17	18.02	28.68	450.26	488.67	13.14	14.43
Y1	short	cowpea & sudax	6.58	6.97	215.34	215	5.98	8.39	17.43	22.34	424.53	384.74	13.58	12.54
Y1	short	sunn hemp	7.46	7.55	199.6	211.74	7.46	10.25	17.63	15.84 *	425.62	455	11.08	12.19
Y1	long	bare control	7.82	7.13	218.76	214.91	8.87	7.98	18.09	20.23	392.93	358.38	11.63	10.01
Y1	long	buckwheat	7.58	9.34	215.25	224.34	8.24	10.29	18.63	23.55	511.53	491.7	14.04	15.17 *
Y1	long	vetch & sudax	6.69	8.76	217.29	252.19	7.49	10.54	18.88	24.15	477.53	466.17	12.93	13.9
Y1	long	cowpea & sudax	6.84	6.72	172.37	165.6	7.83	8.14	17.31	28.16	467.25	454.46	11.33	14.57
Y1	long	sunn hemp	7.73	7.38	220.55	241.57	7.1	8.35	16.17	19.69	406.21	419.32	11.87	12.41
Y2	short	bare control	15.84	14.99	159.4	183.92	12.91	8.4	25.73	23	453.03	497.14	12.94	11.22
Y2	short	buckwheat	38.81 ***	15.77	201.86	188.7	14.32	9.57	25.59	23.09	499.22	514.16	13.71	10.88
Y2	short	vetch & sudax	14.26	13.78	165.24	192.03	14.17	9.59	26	24.96	488.11	505.13	14.09	10.6
Y2	short	cowpea & sudax	13.63	13.01	177.03	199.71	15.22	6.89	26.54	26.83	507.15	548.95	13.39	11.02
Y2	short	sunn hemp	15.18	14.88	182.06	194.22	15.37	9.97	26.69	25.81	464.37	538.19	12.32	11.58
Y2	long	bare control	15.91	15.64	203.03	226.68	14.72	10.82	29.28	25.38	548.45	541.64	16.44	9.87
Y2	long	buckwheat	17.56	16.97	189.56	209.13	14.47	10.78	25.92	27.21	497.22	527.39	14.19	11.79
Y2	long	vetch & sudax	16.04	17.65	176.01	208.17	13.81	8.8	24.67	27.16	427.49	479.06	13.44	12.24
Y2	long	cowpea & sudax	22.27	17.14	178.23	197.33	14.09	10.53	28.21	28.07	497.95	544.98	14.24	13.86
Y2	long	sunn hemp	16.62	16.25	172.04	223.98	14.77	10.77	29.36	27.75	523.65	507.02	15.05	15.54

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[15] Stars indicate that the value is significantly different from the bare plot values (* $p<0.05$, ** $p< 0.01$, *** $p<0.001$)

CHAPTER 4. HORIZONTALISM AND WISDOM DIALOGUES TO BUILD TRUST: A CASE STUDY OF COLLABORATION WITH AN IMMIGRANT FARMER COOPERATIVE IN MINNESOTA

Summary

Collaboration between farmers and other food systems professionals is a critical tool for food systems transformation. Collaborative research and outreach can address structural inequalities that limit the success of immigrant and minority growers and uplift the knowledge of farmers, which has been systemically valued below that of academic knowledge. Agroecologists who work at the synthesis of science, movement, and practice propose wisdom dialogues and horizontalism as principles by which to develop collaborations that avoid reinforcing structural inequalities due to race, gender, and traditions of valuing academic knowledge above that of farmers. The current case study examines the potential for wisdom dialogues and horizontal learning in the collaborations with groups of Latinx farmers in the Upper Midwest. We used a qualitative interview approach to examine the motivations, resources, and effects of food systems professionals who work for the University of Minnesota Extension, Department of Agriculture, and an agricultural non-profit. Emergent themes from the interviews included a strong commitment to providing access to knowledge and resources, and recognition that collaboration improved the ability to accomplish institutional goals. Interviewees also acknowledged that institutional support was an important determinant for how much they could prioritize relationships and collaboration in their work. Based on the interviewees' experiences, wisdom dialogues could be important for understanding and acting upon different approaches to equity and equality, and for developing more intentional and mutually beneficial collaborations.

Introduction

Collaboration between farmers and other food systems professionals is a critical tool for food systems transformation. Collaborative research and outreach can address structural inequalities that limit the success of immigrant and minority growers and uplift the knowledge of farmers. In Minnesota, many immigrant farmers have had limited relationships with researchers. How can this gap in practice be addressed? One method is to learn from the attitudes and practices of non-research relationships that university Extension and government agencies have built with farmers.

Literature Review

Society asks farmers in the 21st century to manage their farms for the production of abundant, sanitary, and nutritious food while concomitantly supporting ecosystem function and operating as an economically viable enterprise (Garnett et al., 2013; Hunter et al., 2017). This is a huge task, and one that farmers should not be expected to accomplish on their ingenuity alone. However, efforts to address these complex, interrelated priorities should honor farmer expertise and wisdom. One opportunity to develop knowledge across types of expertise is through sustained collaboration between farmers, academics, and other food systems professionals.

Integrated projects in which academics collaborate with non-academic stakeholders have become more prevalent in recent years under the auspices of participatory and engaged scholarship (Boyer, 1990; Driscoll and Sandmann, 2001). The connection between academic and non-academic knowledge in agriculture has traditionally taken place under the auspices of Land- Grant University (LGU) extension programs. The extension system has a contested history (Peters, 2013), in which its main functional role has been as a technical expert system to share scientific information from academia with farmers (Heleba et al., 2016). However, that position has changed significantly over time, and there are currently efforts to re-think the relationship between research and farmers broadly (Warner, 2006), and to reconsider the historic and future role of extension in such relationships (Peters, 2014).

Key aspects for how to reimagine the role of extension include proposals to re-orient the land grant mission toward broader public accountability, to focus on democratic engagement and in agricultural contexts, on the development of robust, multi-sector networks that promote social learning. Social learning is distinct from the knowledge-transmission model of extension which has been extensively critiqued (McDowell, 2001). However, some see the extension system as a possible hub facilitating broad collaboration and democratic participation in the process of knowledge co-creation and exchange [Warner2006a]. These reorientations have also been more broadly conceptualized in progressive visions of the LGU mission in the 21st century, which defines public accountability as ensuring accessibility, relevance to rural and urban demographics, and focusing on sustainability and social justice (Goldstein et al., 2019).

Proposals to re-think extension and the public role of LGUs are part of the broader international agroecology movement. While a contested term, agroecology in its most transdisciplinary sense seeks to connect farmers, food systems activists, and researchers through integration of the biophysical, social, and political factors in agroecological systems (Altieri, 1987; Wezel et al., 2009). Some people in agroecology use participatory approaches, specifically recognizing that farmer expertise is a critical component in developing more sustainable agroecosystems (Pretty, 1995; Fliert and

Braun, 2002; Berthet et al., 2016; Lacombe et al., 2018). It is also a practical means to allow non-farmers to connect their expertise to the knowledge-sharing networks through which farmers get most of their information (Kroma and Flora, 2001).

Knowledge-sharing and knowledge co-creation in agroecology are facilitated by principles of horizontalism and *diálogo de saberes*, or wisdom dialogues (Anderson et al., 2018). Horizontalism rejects hierarchical transfers of knowledge in favor of peer-to-peer level learning that builds capacity and expertise simultaneously. Wisdom dialogues entail sharing cultural capital, or wisdom, across different groups, thereby building social capital within the larger, combined group (Gutiérrez-Montes and Aguero, 2016). Putting wisdom in dialogue is to engage in respectful appreciation of others' perspectives, and to share one's own wisdom in the process, thereby building collective wisdom. Wisdom dialogues can be farmer-to-farmer, such as farmer field schools in the Mesoamerican Agroenvironmental Project (Gutiérrez-Montes and Aguero, 2016), or can be applied to sharing knowledge across the researcher-farmer divide as is taking place across a diverse set of projects in Europe (Anderson et al., 2018).

Horizontalism and wisdom dialogues are a means to uplift silenced voices, and to provide for "emergent discourses" outside of traditional knowledge (Martínez-Torres and Rosset, 2014; Anderson et al., 2018). Emergent discourses refer to the possibility of new ways to view the world that would not be possible without the unique perspectives offered by participants in the process. By making this space, alternative models of research become possible, which may be more appropriate for engagement with historically marginalized communities. Examples of alternative ways of knowing come from indigenous models of research, which emphasizes relational ways of knowing (Hart, 2010). A relational orientation is built on trust, which has been demonstrably important for successful co-management of natural resources (Stern and Coleman, 2015). Trust can also provide space to explore mutual benefit and reciprocity in the collaboration, which have been key in developing community-based participatory research projects (Jordan and Gust, 2010). Wisdom dialogues can also facilitate shared control and leadership (Lacombe et al., 2018), reflexivity (Finlay, 2002), and development of robust and flexible participatory processes (Lyon et al., 2010).

An approach to building collaborations with farmers using wisdom dialogues and horizontal learning presents a renewed opportunity to address persistent gaps in traditional models of extension and outreach in academia and government. Historically, both academia and the USDA have failed to fulfill their stated missions in interactions with farmers who are not traditionally mainstream. At best, extension and outreach programs have insufficient capacity to address concerns that are not easily defined by traditional disciplines within scientific and technical terms (Peters and Wals, 2013). However, extension and outreach programs have also explicitly sought to disempower and disenfranchise farmers (Scott and Barnett, 2009) based on production practices (Barbercheck et al., 2012), race, gender, or immigration status (Herren and Edwards, 2002; Minkoff-Zern and Sloat, 2016). These conditions have contributed to broader structural barriers for immigrant and minority farmers, who are more likely to have farms with less fertile soil because of historically limited accessibility to land and capital (Sullivan and Peterson, 2015; Minkoff-Zern, 2017).

The historical failures to connect with multiple types of marginalized farmers has resulted in extension and government outreach systems that many immigrant and minority farmers do not see as resources or potential collaborators. In the Upper Midwest, a survey of Hmong and Hispanic farmers indicated that only 2-7% of these farmers would turn to an extension agent or university entity for advice about farming practices (McCamant, 2014). In the Mid-Atlantic region, the growing population of Latino farmers rarely participates in USDA financial assistance programs due to the lack of legibility that their production systems have within the regulatory framework of the USDA programs (Minkoff-Zern and Sloat, 2016). A horticultural extension needs assessment from the University of Minnesota in 2019 found it difficult to reach immigrant farming populations (Klodd and Hoidal, 2019), which may have been due to insufficient alternative language and format outreach.

The persistent lack of connection that academic and government entities have with immigrant and minority farmers heightens the risk that alternative food movements or extension reforms may not address underlying systemic problems. For example, in Minnesota, a local purchasing initiative at the University of Minnesota, Duluth campus defined “local” in such a way that indigenous farming communities, on whose stolen land the university is built, were excluded from the benefits of the initiative (Olds et al., 2019). Throughout the US, organic agriculture, farm internship programs, and local food initiatives have been criticized for failing to upend structural racism and inequity (Slocum, 2007; Guthman, 2008; Etmanski, 2012; Cadieux et al., 2019; Levkoe, 2019).

It is therefore clear that the force of good intentions and theoretical commitments to wisdom dialogues and horizontal learning are insufficient. As has been proposed in the literature comparing how food sovereignty and food justice are used in academia, more clarity is needed on what it looks like to “do” the work (Cadieux and Slocum, 2015). In the US, agroecology has been often conceptualized in mostly scientific terms (Wezel et al., 2009; Tomich et al., 2011), while the social movement aspects have been undervalued or undermined (Fernandez et al., 2013). Given this continued contestation, much of the collaborative work undertaken with farmers in the US may not appear to qualify as agroecology on the surface. However, on-the-ground descriptions of and reflection on the practice of collaboration and attempts to operationalize the grand theories of transformational change can move the work into the realm of action research advocated for within agroecology (Méndez et al., 2016). Part of the action research process is the cultivation of a reflective practitioner's posture, in which participants engage in self-reflection and critique of their participation, thus expanding agency for change (Reason and Torbert, 2001; Torbert, 2001). It is in the spirit of reflection that the following case study is offered.

Working toward wisdom dialogues in Minnesota: Vegetable Farming and Collaborative Knowledge Creation

The Minnesota Department of Agriculture Specialty Crop Block Grant Program is a fund specifically designated for research that advances the economic viability of specialty crop enterprises in Minnesota. The program emphasizes funding projects that serve socially disadvantaged farmers (Minnesota Department of Agriculture, 2020). In 2016, a collaborative project was funded to "develop partnerships between the University of Minnesota and established community organizations for sustained outreach to immigrant farmers in Minnesota", while also increasing access to knowledge about specialty vegetable production through assessment of the agronomic potential of growing a summer cover crop (a non-harvested crop grown to protect soil and help with fertility) before a fall-planted cash crop.

The main focus of the MDA grant was to gather in-depth quantitative measurements of cover crop vigor, soil health changes, and economic impacts, with partnership-building as an intended but largely unplanned outcome of project co-design, data collection, and associated outreach activities. Specifically, the project was proposed as a means to strengthen a nascent partnership between the University of Minnesota and an established cooperative of majority Latinx farmers, but without a specific theory of change to accomplish this goal. As the lead researcher on the project, I joined the project with two additional goals. First, as a former farmer having recently become a researcher at the university, I sought to make the research project design, implementation, and interpretation to be particularly attendant to the knowledge and expertise of the farmers with whom I worked. In doing so, I hoped that my research would include horizontal learning and wisdom dialogues that would challenge the traditional supremacy of academic knowledge above the knowledge of farmers and thus allow for emergent discourse on the future of the farming systems that farmers I worked with managed. Second, as a graduate student, I wanted to proactively address the fact that I would only be at the university for a few years, potentially limiting the opportunity for adequate attention to relational people-focused project development. While the project was originally conceived as a collaboration between a cooperative of Latinx farmers and a researcher who wrote the grant for the project, I had not been part of that process and had no existing relationships with the cooperative.

My goals to push back against academic supremacy and prioritize relationships in the research project had uneven success. In many ways, the biophysically-focused research project followed fairly traditional protocols for design and data collection, though with significant farmer input, management, and preliminary analysis of the results, as well as outreach. The difficulties and messiness of moving beyond traditional biophysical research project designs led to collaborative exploration between me and the farmers about what personal and structural conditions could facilitate future collaboration. Specifically, in the absence of previous collaboration, and mutual recognition of the potentially discontinuous nature of research collaborations, our conversations highlighted the critical importance of long-term relationships, such as farmers more often have with non-research entities like University Extension, state Departments of Agriculture, and nonprofits.

The farmers in the cooperative repeatedly stressed the importance of non-research-focused collaborations to the success of farmers, because of the potential for long-term interaction and access to resources that such collaboration can facilitate. Therefore, in the absence of prior research relationships, our goal was to elaborate on approaches and mental habits that current government and academic representatives currently have when working with individuals from the farming cooperative, to inform those same practices, and potential future research collaboration. The current case study explores the goals, capacities, and attitudes of non-research-focused collaborators who work with this cooperative of farmers. It uses the concepts of wisdom dialogues and horizontalism as principles by which to evaluate the relationships in collaborations. In doing so, I focus on current collaborators who work with farmers from this cooperative to learn from their successes and to build upon that knowledge to suggest important growth areas to facilitate future collaboration.

Methods

Individuals in the case study are all non-farmer food system professionals identified as current collaborators with the farmers in the cooperative. These professionals are employed by the University of Minnesota (5), Minnesota Department of Agriculture (2), and a non-governmental organization (NGO) (1).

The technique used in the study was semi-structured interviews, which strike a balance between affording individual interviewees the opportunity to express their opinions and mental habits and maintaining comparability across multiple interviews (Adams, 2015). I conducted eight interviews of 35-65 minutes each. The interview questions focused on aspects of collaboration or potential collaboration with immigrant farmers. Specifically, interviewees were asked about their (and their organizations') goals for collaboration, their role in such collaborations, as well as perceived consequences of not collaborating with these farmers. Additional questions touched on the resources and capacities that individuals or organizations had to collaborate with farmers, and how collaboration has or could change the practice of their work as it related to the future of vegetable farming in the Upper Midwest (Table 4.1).

All interviewees were recorded and transcribed using an automated transcription software service (Temi, 2020). Subsequently, the author reviewed all transcriptions with the original audio and made necessary corrections. Transcriptions were analyzed for emergent themes related to each of the questions. Emergent themes were concepts that were repeated across multiple participants, both in agreement and disagreement.

In the results, I introduce each of the main emergent themes under the topics of Goal, Effects, and Resources. I then discuss how these themes build on existing knowledge about how to appropriately collaborate with farmers, especially those who have been systematically marginalized. I then close with preliminary recommendations based on the interviews that may extend beyond the non-research-focused professional to inform how researchers can be better partners in collaborative knowledge development – thus contributing to the resilience of the farmers and their systems.

Results

Goals: provide access and facilitate co-learning space

Interviewees indicated that their goals when collaborating and engaging with immigrant and minority farmers generally and the farmers of cooperative, in particular, were to facilitate access to information and resources. An additional goal highlighted by the NGO employee and an extension professional was to facilitate a space for co-learning between farmers. While the goal of accessibility was universal among interviewees, individuals varied in how they conceived of accessibility. One conception of accessibility focused on the broad range of resources within the organization, and making sure that the largest possible number of farmers had access to that knowledge:

> My goal, in a very basic sense, is [that] there's so much information out there that can help farmers that they don't currently have access to, and so I want to help them get access to information that they need to be successful, whatever that means to them. (#6)

In contrast, a second approach to providing access through collaboration focused on the diversity of farmers and prioritized making sure that all farmers received equitable access to the organization's resources. One interviewee articulated the importance of carefully identifying and thinking through who the farmers were who might need access; considerations included geographical diversity, farming techniques, farming styles, and farming approaches, crops grown, cultural nuances, racial diversity, as well as other localized forms of marginalization. Beyond considering the various forms of diversity, the interviewee was adamant about the need for appropriate motivations and active follow-through in collaborations and improving access to the aforementioned groups:

> For me what is really, really, important [in my organization] is to make sure that we have very fair and balanced equity in our approach, and in the services that we provide, and in making sure that all Minnesota farmers receive the same level of access, but also resources…And first of all, a lot of people talk about diversity, and having diversity in this and diversity in that, and sometimes, to be frankly honest, I think folks really just want to check a box… It's one thing, which is good, for us to make sure that we recognize [multiple forms of diversity] and want to make sure that everybody is at the table, but what are we doing to make sure that those groups can actually participate at the same level and be provided with whatever resources they need to allow them to participate at that level? (#5)

The same interviewee also strongly advocated that collaboration alone was not a sufficient frame through which to provide access. Rather, it was necessary to have "intentional collaboration", a phrase that was echoed by another interviewee from a different organization. For both, intentionality was linked closely with compensation. The focus on remuneration was echoed by other interviewees who specifically mentioned that grant funding had improved their ability to work directly with farmers because they had written farmer compensation into the grant budget. In describing one collaborative project, the interviewee equated that payment with their impression that the farmers felt respected.

> I tried to make it like we were equal partners and I used grant funds… I mean, I crank our thousands of dollars out the door to them, so I feel that they felt really respected in the process, so that was good. (#3)

Furthermore, multiple interviewees pointed out that collaboration could be an over-commitment to add to the already busy lives of farmers, and that they had taken care to collaborate with farmers in ways that fit within their priorities and schedules. One interviewee provided a specific example of collaboration when they created a farmer advisory board for a curriculum design project. When asking one farmer to be on the board, they specifically did not ask them to write anything or attend specific meetings, but rather to be on call for questions that came up during the project. (#3). At the same time, interviewees also stressed that collaboration was more appropriate and would be more successful at providing access if farmers were involved in collaborative projects as early as possible, not just when the information was being disseminated.

While interviewees primarily sought to collaborate in order to increase farmer access to knowledge from their organizations, they also sought to support and facilitate spaces for co-learning. This goal was connected for some interviewees with the effects of their work, in that collaboration could build trust with farmers and thus facilitate future outreach opportunities. This was illustrated by an interviewee who connected mission accomplishment and trust-building back to the horizontal information-sharing that others had indicated as a goal of their work.

> The more we’re able to build trust with them, and the more comfortable they feel coming to us, then the more information that they’re able to share with their communities and potentially put those people directly in touch with us… we’re meeting our goals because we’ve got accurate information flowing out into communities. (#7)

The interviewee acknowledged that connecting with a single farmer could result in broader outreach that the individual connection might suggest. Each individual connection could be an effective strategy to promote co-learning opportunities among networked farmers, and to provide multiple farmers with resources, even if the collaboration only happened with one person.

Effects & Consequences: relationship-focused & organizational mission accomplishment

Interviewees consistently report that collaboration with immigrant and minority farmers increased their ability to accomplish the organization’s mission. All of the interviewees have farmer engagement as part of their work, and they indicated that by collaborating with farmers, they were better able to accomplish that mission. One interviewee, who had recently started in their position, expressed this sentiment as being dependent on building trust with collaborators, while also acknowledging that their organization had not always been a trustworthy collaborator.

> If no one is trusting the work that we’re putting out, we’re not really doing anything; we’re not really achieving any public benefit. I think there’s a general trend in the world that people are changing the way that we trust authority and people are moving away from this idea that just because [an authority] said it, it must be true. We tend to trust more anecdotal

> information and the people around us, and I think that's fine. I still really believe that research and the process of research is really important to how we understand the world, and I see that the more that we can involve people in that process and allow people to feel empowered in that process, and like they have some say in that process, the more we maybe can build trust in institutions and in research. I know that that has not always been merited, and that [institutions] have done things that have not been in the public interest and that have harmed communities, but I think that by involving people in that research process, we hold ourselves accountable, and we also achieve more public good. (#8)

This statement stressed the potential connections between research opportunities and the long-term, non-research focused relationships that the farmers in the cooperative have with interviewees. By connecting the research process to non-research engagement, the interviewee expressed a desire to build trust across multiple types of knowledge and expertise.

Other interviewees echoed the sentiment that building trust through collaboration was key to organizational success because it made farmers more likely to engage with the organization. Interviewees also mentioned that in the process of building trust, they needed to adjust their job descriptions and, in multiple cases, actively participate in the community without expecting to accomplish any of their role-specific goals. Examples of this type of engagement included attending cultural celebrations (#3), regular meetings of the two main farmer-to-farmer networks in the state (Land Stewardship Project and Sustainable Farming Association) (#3, #6), farmer-focused conferences (#5), and an annual farm-to-school barbecue (#4).

While interviewees felt that building collaborations with farmers of all kinds was critical to the future of their organizational missions, they also expressed an understanding that their choice or desire to collaborate and participate in less traditional outreach model was not universally accepted:

> I would say this style of engagement is the future, but there's still plenty of other people in the world who just want to see the ROI on how our time and money is spent. And so figuring out how we could express that concept of outreach and engagement in a way that really does make sense to everybody because it's, it's not something that people who maybe are not fans of the government [would like]. It's not something that everybody sees that sees the need for. (#7)

Negotiating the negative perceptions of collaborative engagement was an important aspect of the interviewee's work, and for multiple interviewees, this pushback related directly to perceived capacities and resources, as discussed below.

Capacities & Resources: structural unevenness and ongoing self-work

Interviewees consistently mentioned the importance of structural support for collaborative, relationship-focused work. However, each person felt different levels of support from none, to passive encouragement, to active support (Figure 4.1).

The main types of support interviewees highlighted included practical considerations like time, funding, and scheduling flexibility, as well as more abstract concepts of a supportive culture and understanding of how to do collaborative work. While interviewees varied on the extent to which they felt supported, all felt like their institutional conditions did not materially prevent them from engaging in this type of work. One interviewee described the difference between official policy and how the relationship with their supervisors affected the actual process of their work:

> We're not supposed to be one-on-one. That is also most exclusively forbidden…[but] I say, pay attention to the results, let me deal with the process… and that's what's happened. So [my supervisor] has basically said, whatever you're doing, keep doing it. So I really appreciate that. I mean it's amazing, we have no oversight. So in that ways it's good, [but] if you're new, that's hard, because you have very little mentorship. (#3)

On the other end of the spectrum, members of one organization emphasized that their unit was actively supportive of collaborative and relationship-based work that focused on immigrant farmers and valued their knowledge.

> One of the reasons that I feel good about where our program is it's not any single individual within our program that's responsible for ultimately holding up all of those new relationships that we're trying to build… I think what ultimately puts our program on a really good track is the fact that [our supervisor] is also super, super conscious about matters related to race and equity, but also just relationships in general and that need for human interaction and positive relationships with people. (#7)

In addition to institutional attitudes, multiple interviewees mentioned individual introspection and self-awareness. In general, interviewees described their lack of confidence working with immigrant farmers or their organization's lack of history working with this group. Interviewees agreed that university and government entities have not historically had sustained collaboration or even “community presence”. However, one participant also felt that the organizational reputation limited their professional capacity: “it’s like [the organization] is bad. That’s really hard… because I’m not a bad person”. On the other hand, others stressed the importance of “taking your ego out of it” and “getting out of your comfort zone” in order to build relationships.

The final aspect of capacity that emerged as a major theme centered around tangible resources, mainly time and money. As mentioned above, the use of grant funding instead of institution funds often allowed interviewees to work on more collaborative and relationship-focused projects with immigrant farmers. Interviewees mentioned that grant funding could be designated to pay farmers for their time and expertise, which is more difficult with other funding sources. However, grant funding is less secure than other sources of funding, so reliance on it was presented as a source of uncertainty.

Discussion

Collaboration and engagement between the farmers of the cooperative and academics, government, and non-profits remain uneven, but there was a clearly expressed desire to provide access to resources and knowledge and repeated recognition that working with immigrant and minority farmers improves the capacity to accomplish goals. The effects and resources mentioned by interviewees mutually reinforced one another, while the goals and motivation were the backdrop that determined the types of effects and resources sought or prioritized (Figure 4.2).

In general, interviewees were committed to some sort of relational process, and the commitments to creating spaces for co-learning indicate the appreciation for different types of knowledge necessary for horizontal learning and wisdom dialogues. Also, interviewees were well aware of the institutional norms and hierarchical structures that affected their ability to do the work and had divergent approaches to address these. This recognition and strategy also hold potential for creating spaces for the emergent discourses of wisdom dialogues, which could potentially alter goals and motivations for participating in collaborations with farmers. Specifically, wisdom dialogues could be important for understanding and acting upon different approaches to equity and equality, and for developing more intentional and mutually beneficial collaborations.

Tensions between equality and equity

Interviewees generally highlighted that their goal for collaboration and engagement was to provide material and informational access to immigrant and minority farmers. However, the actions necessary to provide access differ widely depending on how an individual or organization defines and evaluates equal access, which can be seen as a choice between "equity" and "equality" approaches. To illustrate the importance of an equity approach one interview specifically mentioned a well-known "equity vs equality" picture, which includes side-by-side pictures indicating that equality is each party getting similar advantages despite their differences, which can reinforce inequality. In contrast, equity entails that each party gets the same outcome supported by different advantages. For the interviewee, this picture served as a visual reminder that providing an identical approach for all farmers was insufficient, and that some farmers needed a different approach to achieve equity. Support for this perspective comes from an analysis of the lack of legibility between Latinx diversified farmers and the USDA in the Mid-Atlantic Region (Minkoff-Zern and Sloat, 2016). In their study, the researchers found that the USDA focus on written records and standardization severely limited participation of

Latinx farmers in cost-share programs. These concerns were echoed by our farmer collaborators, who specifically mentioned that word-to-word translations of information from English to Spanish often was insufficient to make the information accessible to them.

Recognizing that different approaches are more appropriate for collaboration and engagement with different groups is at the core of wisdom dialogues and horizontal learning, because they democratize the style of learning and teaching, and break down barriers between the two. A well-known example of this process is the campesino-a-campesino model in Central America, where farmers trained one another in agroecological practices (Holt-Giménez, 2006). The model approaches learning by scaling out. Knowledge is transferred horizontally, often through grassroots social movement networks (Mier y Terán et al., 2018). In the past decade across the USA, university Extension programs have launched various racial equity initiatives (see, for example, NCSU CEFS Committee on Racial Equity in the Food System, and MSU Center For Regional Food Systems Racial Equity in the Food System Workgroup). Given the desire expressed by interviewees for more explicit training on issues of equity, it will be helpful to track the effectiveness of these initiatives in order to adapt and expand them more broadly across LGUs. More explicit attention on how to build on a racial equity approach using the concept of wisdom dialogues could be helpful to move beyond the goal of increasing access for farmers to learn, but to enrich and transform institutional knowledge by incorporating the wisdom of the farmers.

Intentionality and explicit self-interest

There is a long history of researchers and academic or government agencies using communities for their professional benefit, without reciprocal benefits to the community. The farmers and cooperative advisers provided examples of this as one of the main limitations of working with outside entities. To overcome the lack of trust, potential collaborators must demonstrate their good-faith commitment to reciprocal benefit. In research, one opportunity to do this has been via the development of memorandums of understanding (MOUs), worksheets, and agreements to facilitate an explicit expression of the needs and capacities of all involved. However, even projects specifically designed to address inequalities in food systems struggle to break free from "academic supremacy", or the systematic privileging of academic partners in research collaborations (Porter and Wechsler, 2018). The four main aspects of inequality mentioned in the article – employment conditions, institutional support, capacity development, and autonomy and control of funding – are all relevant to the work discussed here. In non-research contexts, one of the main concerns is that collaboration and engagement are only desirable to check a box or accomplish an external directive. By addressing these factors explicitly and acknowledging the need for all parties in a collaboration to benefit, collaborations can build trust, and potentially redistribute resources such that all collaborators receive what they need from the process.

Careful attention to how trust is developed and demonstrated was the main way the farmers and advisers felt that concerns about motivations could be overcome. As one of the farmers said, "you have to have a structure that in the end builds trust…Does it sound more poetic than theoretical? Yes, but this is one of the parts that I think would be most important for the university to have." While a turn towards the poetic is unusual, if not explicitly frowned upon, in scientific disciplines, this approach is more common in arts and design disciplines, which may have useful resources for creating emergent spaces within scientific discourse. One recent approach evaluated the use of imaginative exercises and scenario-building to facilitate the identification and development of transformative policy (Pereira et al., 2019). Some of the necessary prerequisites to this process includes legitimate stakeholder involvement and inclusion of diverse voices, which could be accomplished via wisdom dialogues. In another approach toward incorporating the poetic aspect of trust into collaboration, non-farmers working on a participatory project have proposed the concept of "emotional rigor" as important to navigate the complexity of participatory collaborative work (Bradley et al., 2018). Specifically, they provide examples of a praxis-from-the-heart, in which emotions related to the work are not seen as separate or tangential to the research process, but a valuable and valid part, and when acknowledged and acted on, can enrich the research process.

Conclusions & insights for practitioners

This case study offers the concepts of wisdom dialogues and horizontalism as tools to think about the successes and limitations of current collaborations between a group of farmers and various non-farmer professionals. While some of the goals and motivations of Extension, government, and nonprofits are compatible with wisdom dialogues and horizontal learning, more can be done to explicitly disrupt structural inequities and prioritization (both implicit and explicit) of knowledge transmission over knowledge co-creation. The study also provided ample evidence of the extent to which many non-farmer food system professionals, even those tasked with outreach to immigrant and minority communities, find that their structural position limits that outreach effectiveness. Based on the experiences of interviewees and my own experience beginning the process of relationship-building for research, I offer a few preliminary insights on how to navigate these challenges:

1. The deep trust-building necessary for effective collaboration is difficult to quantify in scientific disciplines - yet it is absolutely critical. Practice is necessary to develop a deep appreciation of different perspectives that wisdom dialogues require. Some possible ways to fold trust-building into research may include:
    a. Self-guided research; do not expect collaborators to be the sole source of information on their cultural heritage or immigration history. There are many resources available, and doing some self-reflective learning before engagement will alleviate some of the burdens from collaborators.
    b. Conduct on-farm research if the farmer is interested, and during which you may be able to help with on-farm labor.
    c. Attend or volunteer at farmer-focused conferences and workshops, and/or invite collaborators to present (or co-present if they would prefer) in the spaces where you are typically invited to be an expert.
2. Trust-building takes time, and it is critically important to move beyond the idea that farmers should participate pro bono in research activities. Find ways to compensate farmers for their time.

For these recommendations, the implementation may be significantly affected by the level of support available. Clear-eyed evaluation about where supervisors or departments fall on the spectrum from one to active support (Figure 4.1) will affect your strategy when developing partnerships, and may require a adjustments in ambitions and expectations.

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Table 4.1. Question list for semi-structured interviews

Topic	Question
Goals & Motivation	What are yours, or your organization’s goals for working to produce knowledge in collaboration with vegetable farmers who are immigrant, minority, and /or from historically marginalized backgrounds here in the Upper Midwest?
	What would be the consequences of not accomplishing the goals we’ve talked about?
Roles	What role does your organization, and/or you professionally, play in achieving those goals?
Effects	How does, or could collaborating with farmers change the practice of your work as it relates to the future of farming in the Upper Midwest?
Capacity	What capacities/resources do you and your organization have to accomplish these goals, and what resources or changes would you like to see?

We're not supposed to be one-one one. That is almost exclusively forbidden (3)

[My supervisor said] take the time to really figure out where you're most needed" (8)

I think what ultimately puts our program on a really good track is the fact that [our supervisor] is also super, super conscious about matters related to race and equity, but also just relationships in general and that need for human interaction and positive relationships with people.(7)

They're very supportive of me engaging with these groups, but they don't really understand what it takes. (6)

[Supervisors] are all supportive of the work… but their hands are tied, too (by

As far as organizational support or lack thereof, I haven't really felt anything particularly strongly one way or the other. I feel like there's definitely encouragement to work with these audiences, but we don't necessarily have an orientation or materials that are specific for how to go about doing these things. (4)

There's definitely encouragement to work with these audiences, but we don't have an orientation or materials that are specific for

[My supervisor] has basically said, whatever you're doing, keep on doing it… we have no oversight. (3)

Figure 4.1. Types of support offered to interviewees for conducting collaborative work with immigrant and minority farmers

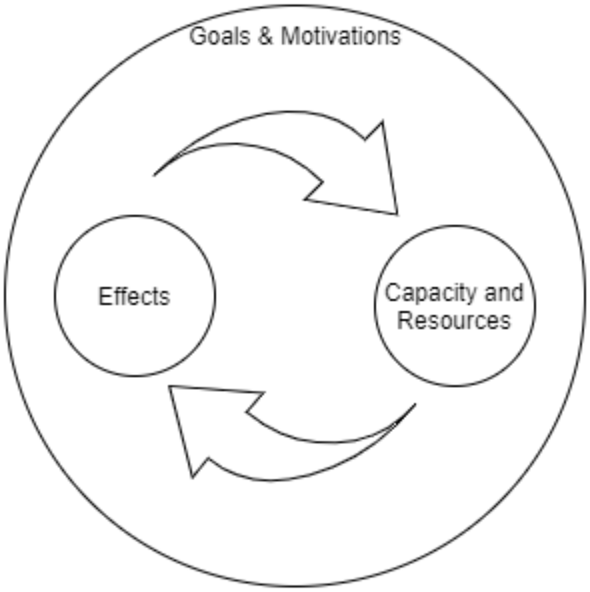

Figure 4.2. Visual representation of the relationship between the capacities and resources that non-farmers have and the effects they hope to or can achieve. Goals and motivations form the backdrop onto which effects and resources mutually reinforce one another. Wisdom dialogues would be most impactful at the level of goals and motivations, thus changing the context in which effects and resources exist and affect one another.

CHAPTER 5. CODA

A thesis coda or conclusion marks the end of the tangible product through which scholars are expected to demonstrate their intellectual merit accumulated through the course of their training as an academic. The dominant model of graduate programs, especially those in the sciences, are designed to provide a structured space (through classes, mentorship, and independent research) in which scholars accumulate knowledge through diligent study of academic literature, then identify a knowledge gap that aligns with the passions of the scholar – and thus a thesis is born. Crucially, in this model, the creativity and transformative possibility of a thesis is an intensely individual task. It is thus limited by the personal accumulation of knowledge, well-described by Paulo Freire as the “banking” model of education (Freire, 2005), which trains us as scientists to only accept as valid that which has already been deemed worthy of inclusion in the academic canon. As a participant in this process, I leave graduate school with a deep foundation of topic-specific knowledge on cover crops and soil nutrient cycling.

Deep knowledge is important. However, this narrow training puts us at risk of a pattern that farmers are often accused of in agricultural research: namely, that farmers take better care of land that they own versus land they rent or otherwise manage with insecure tenure. Recent research in the US and abroad has challenged this claim (Heidi et al., 2019; Frisvold et al., 2020). Land stewardship decisions are more importantly affected by the relationships that farmers have with landowners, with each other, and how they conceptualize soil and plant health. However, if we in academia are trained as knowledge accumulators, we inadvertently create a dichotomy between the knowledge we have and everything else. In this model, the effects and impacts of what we do with our accumulated knowledge is beyond our ownership sphere; the rest of the world becomes just rented land. Creating a boundary between the individual and the rest of the world means that we, not farmers, neglect our responsibility and relationality to knowledge and the world in which it is constructed. As a scientist, I (and perhaps others as well) need to disrupt our sense of individuality and build habits of relational (instead of accumulative) learning into our work, and then act accordingly.

As I have tried to demonstrate in this thesis, agroecology is a set of principles that tries to undo the isolating structures described above, as an integrated combination of science, movement, and practice (Wezel et al., 2009) that is explicitly participatory, transdisciplinary, and action-oriented (Méndez et al., 2016). The framework of agroecology holds promise for developing knowledge with local farmers about managing soil health in vegetable systems, and seemed appropriate to me as an incoming graduate student with a farming background who sought to connect scientific knowledge and farmer expertise. However, the signature pedagogy of agricultural sciences (Shulman, 2005) does not include training in ways of knowing beyond the accumulative process described above, nor in how to build relational knowledge or conduct participatory research. Therefore, what I have learned about this comes from the messy, beautiful process of trial and error with farmers and fellow researchers during the program. Two types of relationships have been particularly impactful in this regard: the first are mentors outside of academia. The second are cohorts.

Mentorship and cohorts have been important in my development as a scholar because they have provided opportunities to learn about and then practice ways of knowing beyond the knowledge accumulation model promoted within academia.

Indigenous scholars have described knowledge as a dynamic relational process in which the person learning is responsible to the knowledge and to the community that has created the possibility of coming into relationship with that knowledge (Wilson, 2008; Hart, 2010; Martens et al., 2016). Global south theorist Boaventura de Sousa Santos elaborated an “ecology of knowledges”, within which each type of knowledge has both an internal and external boundary – that which is not yet known, and that which cannot be known with that type of knowledge (Santos, 2014). In this framework, knowledge and ignorance are not opposite ends of a long line, with learning as a steady accumulation that moves a person from one end to the other. Rather, people exist in relationship to one another, and therefore the ignorance and knowledge of an individual exists as part of a constantly communicating network with other knowledge and ignorance, all of which is constructed in relation to the rest of the world.

My main opportunity to practice relational knowledge building and participatory research has been through on-farm research with members of a cooperative of Latinx farmers, the results of which form the previous chapters of this dissertation. As part of the research process I have been mentored by Rodrigo, the farmer who proposed the research project on summer cover crops. Already an accomplished farmer, farm adviser, and advocate for social justice in agriculture, Rodrigo agreed to host one of my field sites as a paid collaborator, and as such welcomed me onto the farm, both as a scientist and as manual labor to help out when more hands were needed. He was willing to answer questions, to correct me about erroneous assumptions, and to trust me enough to ask me for help when he needed it. One particular instance was when I sent him a proposed presentation about my research. Most of the draft dealt with the biophysical aspects of my research (see Chapters 2 and 3), but I framed the study as important partly because cover crops may be a resource to build soil health for Latinx farmers who more often lack access to stable land tenure and fertile soil. Rodrigo agreed with the content of the presentation, but pushed me to present more about the statistics about who farms in the U.S., and the disparities between predominantly white farm owners and non-white farm workers. It was a small change to the presentation, but an important reminder that to show up as his collaborator meant pushing the boundaries of reductionist science that pretend that the socio-political realities of agricultural systems can be segregated from biophysical research, or that a such a narrow approach to food systems transformation is sufficient for transformation at all.

As part of the cover crop research we collaborated on, I also conducted a case study of other collaborators who work with Rodrigo and other members of a farming collaborative (see Chapter 4). During the preparation for that study, I asked Rodrigo what had been most important to facilitate success in our relationship. Without hesitation, he responded "You respect farmers". He then followed up by suggesting that it was work that I had done in order to be ready to engage respectfully with him, and that I was in a better position to say what I had done than he was. This was not the response I was expecting; I expected him to tell me what actions I had taken within the relationship. Instead, he was able to articulate and honor the work that I had done outside of our relationship, that made me a viable collaborator. This work has taken various forms, such as participating in local leftist organizing movements, in attending talks at the Native American Medicine Garden, participating in roundtable discussions on Decolonization, and supporting efforts that accomplish the reality, and not metaphor, of decolonization

(Tuck and Yang, 2012). Of course, none of these actions are sufficient, and they will never be done. However, my graduate school training on individual scientific knowledge accumulation left no space for me to independently consider this work as part of the necessary preparation for collaboration with farmers. It took a farmer to help me see that. It is my duty and goal as I transition out of graduate school to continue practicing seeking this space for learning, and to cultivate my connection and responsibility to the rest of the world, and to work toward a science that recognizes and honors ecologies of knowledge. I remind myself to look for mentors with whom I can build relationships that will hold me accountable to participate in this work.

As a complement to the importance of mentorship, my graduate experience has also been shaped through collective learning in cohorts. I entered graduate school as part of an interdisciplinary cohort, through which I learned critical theory. I was also part of a program cohort, through which I learned a range of approaches to agricultural research support within the academic system. At the intersection of the two, I was fortunate to join a cohort of students led by members of my lab, who were explicitly interested in bringing different ways of knowing into agricultural disciplines. Participation in conversations that spanned the gap between the worlds of critical theory and agricultural science was formative in structuring my dissertation research, and opening me up to possibilities of other ways of knowing. Throughout my graduate career, this group has evolved – it has grown as new agroecologists enter the university, and shrunk as they graduate. It has changed foci, first a club, then a class, a reading group, a series of workshops, another class, and now once again a club. Through it all, I have had the distinct honor and privilege of building relational knowledge among a group of motivated, critical, and caring people, each of whom brings their wisdom and ways of knowing to our cohort. Over the course of our work together, we have developed a model of agroecology pedagogy – a guide to the sort of learning we would like to have in order to become the agroecologists we would like to be.

There are five facets to the model. The first facet recognizes the importance of the deep disciplinary knowledge that a thesis is designed to recognize, while also recognizing the importance of non-academic experiential knowledge, including positionality. This knowledge forms a pillar in which a scholar is centered; it is the metaphorical location from which a scholar interacts with the world. Orthogonal to the deep pillar of knowledge are three facets of transdisciplinary knowledge to contextualize, enrich, and facilitate action in the world: critical theory, relational politics, and participatory practices. Critical theory is scholarship and knowledge that recognizes the unequal power relationships that influence knowledge, and helps a scholar understand who is at the table and who might be missing. I gained critical theory through participation in a transdisciplinary cohort, through working with the agroecology cohort, and, at the suggestion of the farmer who mentored me, by learning more about farmworkers and institutional racism in the food system. Relational politics consists of learning the skills and mental habits to appreciate the limits of individual wisdom in an ecology of knowledge; it allows scholars to work with people who are at the table and invite others in. Finally, participatory practice gives scholars the toolbox of what to do when at this metaphorical table – how to set up on-farm research plots, for example. Finally, and perhaps most importantly, the model holds a cohort at its center. The cohort is where the synthesis happens, where we come together – whether it is weekly during a class, or monthly during a pandemic – to talk through our doubts, celebrate our successes, and practice our relational approach to knowledge and to one another. For any graduate students who feel called to a different, relational kind of science, look for a cohort. No one should have to do this work alone; this thesis may not exist without the collective articulation of this model. Specifically, the model has provided me with a grounding in the importance of all of the facets of my graduate work, from the traditional lab analysis to participation in organizing and manual labor on farms.

The importance of mentors and cohorts and a different model of pedagogy have left indelible marks on my dissertation, and on me as a person. I hope that I have been able to in some small way reflect that change back to the University. However, in June 2020, my small reflection feels incommensurate in the face of the continued legacies of colonialism, racism, and hegemony within the university. As of this writing, administrators at various levels of the university have made attempts to demonstrate solidarity in the wake of George Floyd's murder, which has made clear how inadequate the current structures and representation at the university are to advance transformative change for racial justice. At the same time, the CFANS college is currently under scrutiny after choosing to not renew the contract of the long-time caretaker of the Native American Medicine Garden (NAMG), Cânté Sütá-Francis Bettelyoun. The lack of renewal was accompanied by a public statement detailing previous successful collaborations between the university and Indigenous tribes. In the statement, CFANS claimed the NAMG as part of the college, and named it "a place of knowledge sharing and connection with the land", without mentioning any of the people who have been its caretakers. The statement from the college has prompted numerous responses, both from Cânté Sütá and the community of people who have known the NAMG and his work, which, among other issues, point to the expropriated land on which the university was funded and founded (Lee et al., 2020) and detail the ongoing pressure of assimilation that Indigenous people face at the university.

I am a part of the system that claims ownership of the NAMG and has erased or forced assimilation on the indigenous people and upholds systems of white supremacy. It is a system which, to address the issues brought up by marginalized people, must be dismantled and transformed in ways that the individualistic training I have received as part of the system makes me ill-equipped to contribute to. However, perhaps through relational ways of knowing, I can be a useful part of the changes in the system, to give back the land, and support different ways of knowing. Academia seems designed to train me to value myself as an individual, worthy only insofar as I can demonstrate the gap that I fill in the tapestry of knowledge. I think that a worthier aspiration is to be one of the fibers, closely knit with others, giving structural integrity to the whole. It is only through recognizing our connection to one another that we can begin to open our eyes and hearts to other ways of knowing.

It is important to note that my proposed turn toward connection and away from individualism are words, and as such incommensurate with actions. Also, while writing about connection, it is important to note that my voice is more easily heard than others, as one belonging to a woman privileged by a system of white supremacy, with U.S. citizenship and generational wealth partly accumulated through the exploitation of indigenous land and people who were kidnapped from Africa and subjected to enslavement. The reflections presented here are not action, but rather a verbalized self-commitment to action and to a relational system of knowledge. Maybe by recognizing ourselves in relationship to knowledge instead of as the creators of it, we will be better prepared to collaborate with the indigenous people whose land we need to give back, with the descendants of enslaved people to whom we owe reparations, and with the farmers trying to steward the long-term health of their soil.

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