2024

An Agroecological Approach To Improving Soil Health Practices On Vermont Vegetable Farms

Rebecca Reed Maden
University of Vermont

AN AGROECOLOGICAL APPROACH TO IMPROVING SOIL HEALTH PRACTICES ON VERMONT VEGETABLE FARMS

A Dissertation Presented

by

Rebecca Reed Maden

to

The Faculty of the Graduate College

of

The University of Vermont

In Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
Specializing in Plant and Soil Science

January, 2024

Defense Date: November 9, 2023
Dissertation Examination Committee:

V. Ernesto Méndez, Ph.D., Advisor
Rachel E. Schattman, Ph.D., Chairperson
Joshua W. Faulkner, Ph.D.
Vernon Grubinger, Ph.D.
Scott C. Merrill, Ph.D.
Holger Hoock, DPhil, Dean of the Graduate College

ABSTRACT

Vermont's vegetable farms are highly valued for their contributions to the state's food system, environment, and communities, yet their continued success is impeded by many challenges. Specifically, soil is a valued and vulnerable resource, but management of it requires knowledge, money, and time. This dissertation applies an agroecological approach to understanding soil health practices on vegetable farms in three distinct studies.

In the first part of this dissertation, data is collected from six on-farm research trials in 2017-2018 to better understand the nitrogen (N) dynamics following two commonly planted legume-grass cover crop mixes: field peas (*Pisum sativum*, var. '4010') and oats (*Avena sativa*, var. 'Kayouga'), seeded in spring; hairy vetch (*Vicia villosa*) and winter rye (*Secale cereale)* seeded in autumn. Understanding the timing and quantity of available N from legume cover crops promises to help growers produce on-farm fertility while reducing inputs of phosphorus-based fertilizers, the overuse of which can harm water quality. The results of this project demonstrate the context specific nature of nutrient dynamics and associated challenges of predicting soil N availability.

The next chapter focuses on a participatory research project to better understand yield outcomes related to newly revised high tunnel tomato nutrient recommendations. This project collected data from 46 farms in Maine, Massachusetts, New York, and Vermont in 2020-2021, revealing that the new recommendations led to predictably better yields, but that on farm practices had a significant impact.

In the final chapter, co-created mental models were used to better understand opportunities and barriers to soil health practice implementation. This project analyzed data from 12 vegetable farmer interviews conducted in spring 2022. The findings revealed that growers were enabled by knowledge, innovation, and peer to peer support, while they were limited by money, land, equipment, and time. This chapter suggests adapting mental models for future Extension and outreach work.

This dissertation highlights the range of soil health practices on Vermont vegetable farms and the associated diversity in metrics and outcomes. Farmers will best be served in the future with support and resources that account for each farm's unique context.

ACKNOWLEDGEMENTS

I owe many thanks to my committee: Ernesto Méndez, thank you for welcoming me into the incredible agroecology community and for your guidance with my graduate work and dissertation. Joshua Faulkner, thank you for inspiring me to conduct applied research and for reminding me that supporting farmers is the end goal. Scott Merrill, thank you for so patiently helping me make sense of data. Rachel Schattman, you are the busiest person I know but you somehow always make space to offer insightful feedback. And Vern Grubinger, I wouldn't have dared to do this without your encouragement. Thank you for your mentorship, friendship, and for all you have done to support the community of growers described in this dissertation.

For all the friends who urged me along and jumped in to help—my heart is full of gratitude.

Thank you to my parents who offer boundless support. And Jonas, Chicory, and Ruthie: thank you for providing me with big reasons to keep working for a healthier agroecosystem.

Finally, thank you amazing farmers. You are my friends and community, and I am forever grateful for all you continue to teach me. And for my dearest farmer-love, Scott, you made this dissertation possible. Thank you.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

According to recent U.S. census of agriculture data, Vermont is home to over 700 vegetable farms with approximately $30 million in annual sales (USDA, 2017). These farms range widely in scale and practices, from intensive 0.1 hectare (ha) operations to highly mechanized farms with over 100 ha. Vermont produce farms are highly valued for the food, jobs, and recreational opportunities they provide communities (Conner et al., 2015; Skog et al., 2018) along with additional public benefits, including “ecosystem services”, which can generate improved water quality, clean air, flood mitigation, and carbon sequestration (Hammond Wagner et al., 2019; White et al., 2022).

Diversified vegetable growers face many challenges to their livelihoods, including market access (Artz & Naeve, 2016; Matts et al., 2016), labor costs (Huang et al., 2022; Weil et al., 2017), land availability (Schattman et al., 2018), and personal and family well-being (Hendrickson, 2005). Inexpensive imported produce has driven down vegetable prices in the US while costs of production have increased (Huang et al., 2022). In other words, small to medium scale vegetable producers face enormous barriers to success when trying to compete due to pressures from the industrial food system (Carlisle et al., 2022).

In addition, farmers are confronted with the climate crisis, which impacts Vermont agriculture with increased rainfall, flooding, milder winters, prolonged drought, and new pests and diseases (Galford et al., 2021; Schattman et al., 2018). Vegetable farmers in Vermont have already experienced dramatic losses due to climate events, most notably due to flooding from 2011’s Tropical Storm Irene (Grubinger, 2011; Schattman et al., 2018), and the multiple severe weather incidents in 2023 (VAAFM, 2023). In order to survive—and thrive—in the years ahead, vegetable producers must have the practices and resources to swiftly adapt to these extremes and variability.

The field of agroecology offers mechanisms and leverage points for farms to adapt in the face of new challenges, integrating the science and practice of agriculture with social and political dimensions (Wezel et al., 2009, 2020a). Agroecological scholars have described pathways towards resilience by reducing harmful inputs, crafting a 'new' set of ecological processes, re-establishing connections between those who grow food and those who eat it, and more broadly advocating for a food system based on equity, participation, democracy, and justice (Gliessman, 2016). However, as described above, farmers face substantial political, socio-cultural, economic, environmental, or technological barriers to agroecological practice adoption (Caswell et al., 2021; Wezel et al., 2020b), which are also known as "lock-ins" of industrial agriculture (International Panel of Experts on Sustainable Food Systems, 2016).

Soil health is an important focal point embedded in agroecological approaches, as it is foundational to crop production. Identifying key practices and addressing barriers to soil health practice adoption is a critical precursor to further agroecological transition (Neher et al., 2022; White et al., 2022). Previous literature has demonstrated that outcomes from soil health practices on vegetable farms are highly context dependent and related to multiple other biophysical and social factors (Bruce et al., 2021; Carlisle, 2016; Knewtson et al., 2010; Prager & Curfs, 2016; Schröder et al., 2016). Understanding farmer approaches towards soil health can reveal motivations towards environmental stewardship and agroecology more broadly (Prager & Curfs, 2016; van Hulst et al., 2020).

This doctoral dissertation applies an agroecological lens to examine several key soil health practices on Vermont vegetable farms. It is structured into three core chapters and an integrative conclusion. Chapter Two examines the utilization of legume cover crops as a source of cash crop nitrogen in place of high phosphorus amendments that potentially contribute to surface water degradation. This chapter uses data from replicated research plots on multiple farms to explore soil-nutrient-crop dynamics. Chapter Three implements a participatory approach to understanding outcomes from the implementation of new high tunnel nutrient recommendations. This chapter explores the intersection of soil nutrients, farm practices, site specific factors, and yield outcomes. In Chapter Four, semi-structured interviews and co-created mental models were conducted with twelve vegetable farmers to explore the supporting and disabling mechanisms underlying soil health practice implementation. Applying mental models to farmers' conceptions of soil health reveals the connections that exist between physical, social, economic, and personal realms. The final concluding chapter offers a cohesive summary that emphasizes the importance of integrating farm-specific contexts into technical assistance and Extension outreach. The goal of this dissertation is to offer a scientific, participatory, and agroecological approach that can be used to help Vermont vegetable farms thrive in years to come.

1.2 References

Artz, G., & Naeve, L. (2016). The Benefits and Challenges of Machinery Sharing Among Small-scale Fruit and Vegetable Growers. *Journal of Agriculture, Food Systems,* *and Community Development*, *6*(3), Article 3. https://doi.org/10.5304/jafscd.2016.063.003

Bruce, A. B., Maynard, E. T., Valliant, J. C. D., & Farmer, J. R. (2021). Farm Type and High Tunnel Management: Connections between Farm Characteristics and High Tunnel Outcomes in Indiana. *HortTechnology*, *31*(5), 566–576. https://doi.org/10.21273/HORTTECH04783-21

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

Carlisle, L., Esquivel, K., Baur, P., Ichikawa, N. F., Olimpi, E. M., Ory, J., Waterhouse, H., Iles, A., Karp, D. S., Kremen, C., & Bowles, T. M. (2022). Organic farmers face persistent barriers to adopting diversification practices in California's Central Coast. *Agroecology and Sustainable Food Systems*, *46*(8), 1145–1172. https://doi.org/10.1080/21683565.2022.2104420

Caswell, M., Maden, R., McCune, N., Mendez, V., Bucini, G., Anderzen, J., Izzo, V., Hurley, S. E., Gould, R. K., Faulkner, J. W., & Juncos-Gautier, M. (2021). Amplifying Agroecology in Vermont: Principles and Processes to Foster Food Systems Sustainability. *USDA Agricultural Research Service (ARS) Center*. https://scholarworks.uvm.edu/arsfoodsystems/4

Conner, D., DeWitt, R.-L., Inwood, S., & Archer, M. (2015). Social Responsibility and Community Development in Vermont's Food Business. *Journal of Food Research*, *4*, 93. https://doi.org/10.5539/jfr.v4n6p93

Galford, G. L., Faulkner, J., Dupigny-Giroux, L.-A., Posner, S., & Edling, L. (2021). *Vermont Climate Assessment*. Retrieved on September 9, 2023 from https://site.uvm.edu/vtclimateassessment/

Grubinger, V. P. (2011). Impact of Tropical Storm Irene on Vermont Agriculture. Retrieved October 1, 2023 from http://www.uvm.edu/vtvegandberry/factsheets

Hammond Wagner, C., Gourevitch, J., Horner, K., Kinnebrew, E., Maden, B., Recchia, E., White, A., Wiegman, A., Ricketts, T., Roy Citation Hammond Wagner, E., Livingston, G., Markowitz, D., Audet, M., Ross, C., Kamman, N., Rupe, M., Magnan, M., Faulkner, J., Albee, R., … Koliba, C. (2019). *Issue Paper Payment for Ecosystem Services for Vermont*.

Hendrickson, J. (2005). *Grower to grower: Creating a livelihood on a fresh market vegetable farm*. http://www.cias.wisc.edu/wp-content/uploads/2008/07/grwr2grwr.pdf

Huang, K.-M., Guan, Z., & Hammami, A. (2022). The U.S. Fresh Fruit and Vegetable Industry: An Overview of Production and Trade. *Agriculture*, *12*(10), Article 10. https://doi.org/10.3390/agriculture12101719

International Panel of Experts on Sustainable Food Systems. (2016). *IPES-Food. (2016). From uniformity to diversity: A paradigm shift from industrial agriculture to diversified agroecological systems.* (IPES). http://www.ipes-food.org

Knewtson, S. J. B., Carey, E. E., & Kirkham, M. B. (2010). Management Practices of Growers Using High Tunnels in the Central Great Plains of the United States. *HortTechnology*, *20*(3), 639–645. https://doi.org/10.21273/HORTTECH.20.3.639

Matts, C., Conner, D. S., Fisher, C., Tyler, S., & Hamm, M. W. (2016). Farmer perspectives of Farm to Institution in Michigan: 2012 survey results of vegetable farmers. *Renewable Agriculture and Food Systems*, *31*(1), 60–71. https://doi.org/10.1017/S1742170514000465

Neher, D., & Horner, K. (n.d.). *Resilient Soils for Resilient Farms: An Integrative Approach to Assess, Promote and Value Soil Health for Small- and Medium-Size Farms*. 17.

Prager, K., & Curfs, M. (2016). Using mental models to understand soil management. *Soil Use and Management*, *32*(1), 36–44. https://doi.org/10.1111/sum.12244

Schattman, R. E., Méndez, V. E., Merrill, S. C., & Zia, A. (2018). Mixed methods approach to understanding farmer and agricultural advisor perceptions of climate change and adaptation in Vermont, United States. *Agroecology and Sustainable Food Systems*, *42*(2), 121–148. https://doi.org/10.1080/21683565.2017.1357667

Schröder, J. J., Schulte, R. P. O., Creamer, R. E., Delgado, A., van Leeuwen, J., Lehtinen, T., Rutgers, M., Spiegel, H., Staes, J., Tóth, G., & Wall, D. P. (2016). The elusive role of soil quality in nutrient cycling: A review. *Soil Use and Management*, *32*(4), 476–486. https://doi.org/10.1111/sum.12288

Skog, K. L., Eriksen, S. E., Brekken, C. A., & Francis, C. (2018). Building Resilience in Social-Ecological Food Systems in Vermont. *Sustainability*, *10*(12), Article 12. https://doi.org/10.3390/su10124813

USDA. (2017). *USDA - National Agricultural Statistics Service—2017 Census of Agriculture—Volume 1, Chapter 1: State Level Data*. https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_State_Level/Vermont/

VAAFM. (2023). *Interim Survey Data Highlights Severe Weather Impacts for Vermont Agriculture | Agency of Agriculture Food and Markets*.

https://agriculture.vermont.gov/agency-agriculture-food-markets-news/interim-survey-data-highlights-severe-weather-impacts-vermont

van Hulst, F., Ellis, R., Prager, K., & Msika, J. (2020). Using co-constructed mental models to understand stakeholder perspectives on agro-ecology. *International Journal of Agricultural Sustainability*, *18*(2), 172–195. https://doi.org/10.1080/14735903.2020.1743553

Weil, R. J., Silva, E. M., Hendrickson, J., & Mitchell, P. D. (2017). Time and Technique Studies for Assessing Labor Productivity on Diversified Organic Vegetable Farms. *Journal of Agriculture, Food Systems, and Community Development*, *7*(4), Article 4. https://doi.org/10.5304/jafscd.2017.074.007

Wezel, A., Bellon, S., Doré, T., Francis, C., Vallod, D., & David, C. (2009). Agroecology as a science, a movement and a practice. A review. *Agronomy for Sustainable Development*, *29*(4), 503–515. https://doi.org/10.1051/agro/2009004

Wezel, A., Herren, B. G., Kerr, R. B., Barrios, E., Gonçalves, A. L. R., & Sinclair, F. (2020a). Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agronomy for Sustainable Development*, *40*(6), 40. https://doi.org/10.1007/s13593-020-00646-z

Wezel, A., Herren, B. G., Kerr, R. B., Barrios, E., Gonçalves, A. L. R., & Sinclair, F. (2020b). Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agronomy for Sustainable Development*, *40*(6), 40. https://doi.org/10.1007/s13593-020-00646-z

White, A., Faulkner, J., Conner, D., Méndez, V., & Niles, M. (2022). “How can you put a price on the environment?” Farmer perspectives on stewardship and payment for ecosystem services. *Journal of Soil and Water Conservation*, 00041. https://doi.org/10.2489/jswc.2022.00041

CHAPTER 2: UNDERSTANDING NITROGEN AVAILABILITY FROM LEGUME COVER CROPS ON VERMONT VEGETABLE FARMS

2.1 Introduction

The majority of Vermont vegetable and berry farmers are careful stewards of the land, focused on building soil health for climate resilience, crop outcomes, and broader benefits to the ecosystem (Horner, 2023; R. E. Schattman et al., 2018; White et al., 2018). Until recently, one strategy that both organic and conventional growers in Vermont have employed to improve soil health has been applying dairy or poultry manure and/ or manure-based amendments (such as compost or pelletized poultry manure fertilizer). These materials provide many benefits to the agroecosystem because they add carbon to the soil and provide a well-balanced range of macro and micronutrients for crop uptake, including relatively even proportions of nitrogen (N), phosphorus (P), and potassium (K) (Rosen & Allan, 2007; Warman, 2005). These materials are affordable and often locally sourced, closing the nutrient loop and helping farms recycle a potential "waste" product. These products reduce vegetable and berry farmers' reliance on imported mined minerals, other materials that are transported long distances, or materials produced in unsustainable ways.

Over time, the use of manure and manure-based amendments has led to an abundance, and at times an excess, of phosphorus in the soil on many vegetable farms. This is because crop utilization of the N-P-K nutrients from manure-based amendments rarely matches the exact proportions of the material. In the past, farmers typically applied these amendments to meet the N needs of crops, which quickly led to excessive amounts of P. For example, many growers commonly apply an affordable, local poultry manure with an N-P-K analysis of 2-3-2 (percent by weight), typically applying 3.5 to 4.5 metric tons of manure per hectare to provide the 90 to 110 kg of available N utilized by a vegetable crop (50-60% of N is available year 1). This rate of chicken manure also contributes an ideal amount of potassium to be utilized by most cash crops (180 to 220 kg ha^{-1}). However, the amount of phosphorus in this typical chicken manure application is 270 to 335 kg ha^{-1}, which far exceeds annual P recommendations for vegetable crops (maximum 110-170 kg ha^{-1}). These applications quickly outpace vegetable crop P removal rates, which range from 22 kg ha^{-1} (beans, carrots, onions) to 60 kg ha^{-1} (field tomatoes, cucumbers, potatoes) (B. Sideman et al., 2023). When phosphorus is applied in excess of plant uptake, only a small fraction of it is available as inorganic, or soluble, P. The remainder is quickly immobilized, or adsorbed, onto soil particles by binding on clay surfaces or the iron (Fe) and aluminum (Al) oxides and hydroxides present in soil (Prasad & Chakraborty, 2019). For farmers adding manure-based products, this means that much of the phosphorus in amendments remains locked in the soil, increasing soil P levels year after year. Within a relatively short time, soil P levels can be high enough to meet or exceed annual vegetable crop needs with no additional P inputs recommended.

Excessive phosphorus can become a major pollutant that impairs water quality when it is transported to surface water via run-off or erosion events, or more rarely, when at very high concentrations, it can be lost through leaching (Haygarth & Jarvis, 2002; Magdoff & Van Es, 1993). Toxic blooms of cyanobacteria can result from excessive phosphorus, especially when combined with warm, calm water conditions, which are increasing in frequency due to climate change (Lake Champlain Basin Program, 2022). This has become a critical environmental issue in Vermont, especially on Lake Champlain, where beach closures and restricted lake access have become a regular occurrence in recent years. Agriculture in Vermont is estimated to be responsible for 38% of the phosphorus inputs, primarily originating from applied manure or fertilizers that are washed with soil into the lake during rain events (Lake Champlain Basin Program, 2022.) As climate change brings increasingly erratic, heavy rainstorms and warmer winters, nutrient losses from erosion will continue to increase unless dramatic improvements are made to the nutrient management of agricultural soils (Helling et al., 2015; Mason et al., 2021; Seybold et al., 2022).

To address the issue, the state of Vermont enacted the Required Agricultural Practices (RAPs) in 2016, which "are intended to improve the quality of Vermont's waters by reducing and eliminating cropland erosion, sediment losses, and nutrient losses through improved farm management techniques, technical and compliance assistance, and where appropriate, enforcement" (Vermont Agency of Agriculture Food and Markets, 2016). The RAPs establish nutrient, manure, and waste storage standards, make recommendations for soil health and establish requirements for vegetated buffer zones and livestock exclusion from surface water. In addition, the RAPs determine standards that farmers must adhere to for nutrient management planning and soil conservation.

Solutions to remediate the phosphorus problem in Vermont have largely focused on dairy farms because they manage most of the agricultural land, and they both produce and apply manure. However, vegetable farms are not exempt from the regulations, and many have very high soil phosphorus from decades of manure-based amendment use. A review of over 7,000 commercial vegetable soil tests conducted between 2015 and 2021 revealed that over one-fourth of the fields tested by the UVM Agricultural and Environmental Testing Lab (AETL) have soil phosphorus levels exceeding the RAPs standard limits of >20 ppm (modified Morgan extract), and over half the fields do not require any additional phosphorus fertilization according to vegetable crop recommendations (>7 ppm, modified Morgan extract) (unpublished data Maden, 2021). In order to comply with the RAPs, farmers with excessive soil P are prohibited from amending with additional P, including in manure, compost, and bagged fertilizers.

Vegetable farmers face many barriers to shifting away from amendments that contain phosphorus, including cost, sourcing, and different nutrient release rates. For organic growers, this shift is particularly challenging, as the cost of shifting away from poultry manures to nitrogen-only bagged amendments is four to five times more expensive (D. M. Sullivan & Heinrich, 2016), potentially costing organic growers an additional $240/ha^{-1}$. Many growers also prefer composted chicken, cow, or horse manure because they are from local farms and an industry by-product, especially compared to an alternative nitrogen source like peanut meal, which has high production costs and must be shipped to Vermont. Finally, switching amendment sources means potentially changing application equipment and learning how a different fertility source behaves under various conditions.

2.1.1 Nitrogen from legume cover crops

Legume cover crops are a compelling alternative to the use of manure-based amendments as a source of nitrogen. Legumes form unique symbiotic relationships with nitrogen-fixing rhizobia soil bacteria. This plant-microbe interaction forms nodules on the roots of the legume, which is where the rhizobia convert atmospheric N into a plant available form (Ferguson et al., 2019). Although a legume sheds some small amounts of N as it is growing, the bulk of the N becomes plant available once the cover crop (CC) is terminated and the plants begin to break down. Both the roots (which are covered in nitrogen nodules) and the above ground portions of the plants are rich in nitrogen.

Most studies suggest that in general, legume cover crops release plant available N for 6-8 weeks following cover crop termination (Liebman et al., 2018; Parr et al., 2011). However, the quantity of N contributed by legumes varies based on species, soil type, climate, growing conditions, populations of soil rhizobia, and background soil N ((Drinkwater & Snapp, 2007; Liebman et al., 2018; Perrone et al., 2020). Furthermore, the method of cover crop termination and the stage of maturity of the cover crop impacts N mineralization (Liebman et al., 2018; Van Den Bossche et al., 2009; Wienhold & Halvorson, 1999). How physically accessible the residue is to microbes, specifically in terms of particle size and placement in the soil, also greatly influences the speed of their activity and subsequent mineralization of N (Jahanzad et al., 2016; Liebman et al., 2018).

2.1.2 Cover crops well suited to Vermont

The amount of N produced by a cover crop is directly proportional to the amount of cover crop biomass (Perrone et al., 2020), which means that in Vermont's shorter growing season, less biomass and subsequent N is likely to be produced from legume cover crops. Most cover crop guides used by farmers are for North America in general, where estimates of above-ground biomass production range between 2000 to 6000 kg N ha^{-1} and total N accumulation 50 to 200 kg ha^{-1} (Shennan, 1992). A commonly grown winter legume in Vermont, hairy vetch, is known to produce 2–8 Mg $ha^{-1}$of biomass across a range of climates (Parr et al., 2011; Perrone et al., 2020; Poffenbarger et al., 2015), but N accumulation is reported to be 23% less (168 kg ha^{-1} vs 217 kg ha^{-1}) (Parr et al., 2011) in northern Wisconsin than in warmer climates (Perrone et al., 2020; Stute & Posner, 1995). Furthermore, colder temperatures such as those in Vermont may have a negative impact on the legume-rhizobia mutualism, resulting in reduced biological N fixation and nodulation (Perkus, 2018; Perrone et al., 2020). In Vermont, there is a short window of opportunity to establish overwintering cover crops in the fall, which amplifies associated biomass limitations in the spring (Darby et al., 2012). Vermont's extreme winter temperatures may also kill overwintered legumes (Perrone et al., 2020).

Previous research conducted to understand N availability from cover crops and organic fertilizers in other climates provides useful guidance for understanding N dynamics in Vermont (Gaskin et al., 2022; Sullivan & Andrews, 2012). This work highlights the dynamic nature of organic N availability from cover crops, which varies based on plant and soil type, moisture, temperature, and microbial activity. In the southeastern US, trials of winter legumes have been shown to potentially provide enough N for subsequent corn crops (Parr et al., 2011; Perrone et al., 2020), with most studies showing a large pulse of mineral N available two to five weeks after termination (Stute &

Posner, 1995). When comparing on farm practices, studies show more rapidly available N in conventional tillage systems than in no till systems due to the reduced particle size and incorporation into the soil environment (Blevins et al., 1990; Liebman et al., 2018; Stute & Posner, 1995). The predictability of N release is further complicated because of the changes in the C:N ratio of the cover crop as it matures, which results in changes in the speed of N mineralization from legume cover crops that in turn alter the alignment of N availability with cash crop demand (Drinkwater & Snapp, 2007; Stute & Posner, 1995). Finally, the same cover crop can have different N release rates depending on the termination strategies used by the farmer and the particle size of the cover crop residue (Perrone et al., 2020). These multiple uncertainties related to timing and availability of N mineralization and subsequent cash crop uptake remain a barrier to adoption for commercial vegetable growers (Liebman et al., 2018; S. Snapp et al., 2015). Due to the context dependent nature of N availability following legume cover crops, there continue to be gaps in the literature that would help identify the timing of N release and how that aligns with cash crop planting time (Liebman et al., 2018; Perrone et al., 2020). In addition, farmers with short growing seasons (like Vermont's), must weigh the opportunity costs of cover cropping land during times when it could be planted into a cash crop (S. Snapp et al., 2015). Not knowing exactly what happens after a legume cover crop is incorporated can have negative environmental consequences as well. For example, nitrate leaching can occur if the timing of N release from cover crops is mismatched with cash crop uptake (Drinkwater & Snapp, 2007; J. R. Heckman, 2002; Stute & Posner, 1995). Although farmers are well aware of the multiple benefits from cover crops, without reliable information specific to the value of N produced by legumes, many are reluctant to grow legumes for this purpose.

2.1.3 Measuring nitrogen

Nitrogen is arguably the most heavily relied upon nutrient from a vegetable production standpoint, yet the complex cyclic nature of N explains why it is such a challenging nutrient to both quantify and predict. Nitrogen appears in many different chemical forms in the soil, each with different properties, plant availability, and potential consequences for the ecosystem (Brady & Weil, 1996). Even without additional fertilization or cover cropping, soils contain a pool of nitrogen, which is in organic compounds and largely unavailable to crops. As these organic compounds are "attacked" by soil microorganisms, they are broken down into more simple amino compounds, released as ammonium ions (NH_4^+), and then can be further converted into nitrate (NO_3^-) (Brady & Weil, 1996). This process is mediated by the environment where soil microbes are present, requiring a mix of oxygen, water, and warm soils (above 20^{o}C) (Magdoff & Van Es, 1993).

In vegetable systems, nitrate-N, or NO^3-N, is the form of nitrogen that is most commonly used for N uptake, and in most annual vegetable soils, pools of NH4+ are converted quickly into NO^3-N (J. Heckman et al., 1995; J. R. Heckman, 2002; Magdoff, 1991). For this reason, most measures of soil N in vegetable cropping systems have focused on NO^3-N, which is also the approach used in this study. The pre-sidedress nitrate test (PSNT) was developed as a tool for conventional field crop growers to better manage fertilizer and reduce nitrate leaching (Magdoff, 1991). The PSNT was specifically developed to offer a prediction as to whether there would be a crop yield response after fertilization (J. Heckman et al., 1995). Many field samples have been used to calibrate the PSNT for field corn growers, helping them save fertilizer costs and reduce leaching (Magdoff, 1991). In more recent years, recommendations for use of the PSNT in diversified vegetable crop systems have been developed (Hartz et al., 2000; Heckman et al., 1995; Heckman, 2002) and used by growers as one of the few affordable tools they have to determine the status of their soil N.

Other methods used by researchers to measure nitrogen exist, such as plant root simulator ion resin probes (Liebman et al., 2018). Tools have also been developed to help growers estimate soil N availability such as in field test strips (Scholefield & Titchen, 1995) or Adapt-N, which uses soil and climate data to predict N availability (Sela et al., 2016). Much of the previous research on N mineralization from cover crops used litter bags to measure decomposition and N release from the cover crop (Wagger, 1989; Wienhold & Halvorson, 1999), while some studies use lab incubation trials (Lawson et al., 2013). There is also an emerging emphasis on understanding the complex plant-microbe-mineral interactions that regulate bioavailable N, rather than focusing solely on inorganic N pools (Grandy et al., 2022). This thinking realigns soil nitrogen management with broader soil health indicators because bioavailable N is derived from organic matter and highly dependent upon plant-microbe interactions (Grandy et al., 2022).

Available soil N is critical for cash crop uptake, so it is important to understand when NO^3-N would be utilized by cash crops. Significant work has been done in field corn systems to understand the synchrony between cover crop legume N availability and cash crop utilization (Stute & Posner, 1995; Wagger, 1989; Zotarelli et al., 2008). For vegetable crops, it is more complicated because N utilization and timing depends on the crop. However, most vegetable crops have three phases of growth, with the second growth phase as a period of rapid growth and biomass accumulation. This is typically the period of highest demand for N, with as much as 50 to 85% of the total N uptake for the growing season utilized (J. R. Heckman, 2002). When exactly this phase occurs depends on the crop type as well as the growing conditions. PSNTs are most effective when taken just before this second phase so that a grower has time to sidedress. If fertilizer is applied too late, it may not be utilized by the plant and can be a source of leaching (Drinkwater & Snapp, 2007; J. R. Heckman, 2002).

It has long been understood that legume cover crops have the potential to contribute significant amounts of plant available nitrogen for cash crop production (Liebman et al., 2018). Previous studies have demonstrated that nitrogen applications can be greatly reduced and even eliminated following a legume cover crop (Parr et al., 2011). However, the timing and duration of this nitrogen availability has been largely unknown, especially on a regional basis (Drinkwater & Snapp, 2007; Sullivan & Andrews, 2012).

2.2 Research objectives

This project was designed to help Vermont vegetable farmers change their fertility practices, specifically by reducing the use of amendments that contain phosphorus, and by complementing these with legume cover crops that meet the nitrogen needs of their crops. The goal was to provide insight into the effect of planting and incorporation date on the nitrogen contribution from legumes, which helps farmers make the most of their investment in cover cropping practices. For this project, two grass-legume mixes, field peas (*Pisum sativum*, var. '4010') with oats (*Avena sativa*, var. 'Kayouga') and hairy vetch (*Vicia villosa*) with winter rye (*Secale cereale*) were selected because legume cover crops are nearly always grown as a biculture in Vermont. These mixes will be referred to as "oat-pea" and "rye-vetch" in this paper. These systems have been shown to improve overall system productivity by providing N through biological fixation and absorbing N (Perrone et al., 2020).

Research was conducted to answer the following questions:

1. Can oat-pea and rye-vetch cover crops supply a predictable quantity of plant available nitrogen (PAN), thereby reducing farmers' reliance on phosphorus-based amendments?
2. How long after incorporation is the nitrogen available to vegetable cash crops (e.g., does the timing of PAN match crop N needs)?
3. Is the Pre-sidedress Nitrate Test (PSNT) a useful tool in predicting N availability? If so, how long after cover crop incorporation should farmers take a PSNT?

2.3 Approach

This research was conducted through a Participatory Action Research (PAR) approach (Méndez et al., 2017). PAR strives to equalize the input of all participants in research projects and is seen as a way to enhance the ability of rural communities to share, improve, and analyze knowledge (López-García et al., 2021). This research was conducted with a modified PAR process due to the short-term nature of grant funding. The farmers recruited for this project had previously expressed interest in this topic over the years, offered guidance and advice in developing the project, and helped with project logistics. Each of the farms contributed invaluable insight into the research.

This project worked closely with farm partners to conduct this research with genuine farm practices (as opposed to ones modified to adapt to the research), so that the findings were relevant and easily transferable to other growers in the region. This meant that the dimensions and size of the research plots were determined by the farmers (0.08 to 0.2 hectares) and managed with their farm equipment. Each farm was selected in a different area of the state to capture variations related to soil, weather, and other site-specific factors.

Six commercial organic farms (certified organic by Vermont Organic Farmers, LLC.) in various locations of Vermont were recruited to host the trial in the fall of 2016, with the goal of successfully collecting a complete data set from four farms each in 2017 and 2018. Previous research has shown a 19% withdrawal rate from projects even when farmers have great interest in the topic (Aare et al., 2021; Roques et al., 2022). Since this project relied on farmer land and equipment in addition to their willingness, we planned on 30% of the farms either withdrawing or having invalid data. Each participating farm signed a letter of commitment and was compensated with a $500 purchase of cover crop seed for use on their farm. In both years, six farms joined the study, but two farms were unable to complete the project.

2.4 Materials and Methods

2.4.1 Site descriptions: climate and soil types.

In the fall of 2016, soil samples from the trial fields were collected using a soil sampling tube at a depth of 15-20 cm. Fifteen to twenty subsamples were taken using a "W" pattern and mixed in a clean bucket. Approximately 240 milliliters of the composite sample were placed in a zip lock bag, labeled, and delivered to the University of Vermont Agricultural and Environmental Testing Lab (UVM-AETL) in Burlington, Vermont. These samples were then shipped to the University of Maine Analytical Lab and Maine Soil Testing Service (UMaine), which conducts the soil nutrient extraction for UVM-AETL. UMaine uses the modified Morgan extract to extract major and minor nutrients. This analysis can be used to predict nutrient availability over the course of a season. UMaine uses methods detailed by Wolf and Beegle (2011) and developed by McIntosh (1969) (McIntosh, 1969; Wolf & Beegle, 2011). The UVM-AETL analyzed the extracts and provided nutrient recommendations for each trial field.

For each site year, GPS coordinates and elevation were determined using Google maps. Soil series, texture, and drainage class were collected through the web soil survey. Soil organic matter was derived from soil test results. Table 1 summarizes site characteristics. For standard soil test results for each site, see Appendix A.

Table 1: Farm site year characteristics

Site-year	GPS coordinates	Soil series & texture	Drainage class	Elevation (m)	SOM (%)
CBF 2017	42.99214°N, 73.20482° W	Pittsfield fine sandy loam	Well drained	274	2
CBF 2018	43.01164° N, 73.19093° W	Hartland silt loam	Well drained	292	3.2
GF-2017	43.85132° N, 73.09092° W	Colton gravelly sandy loam	Excessively drained	97	2.8
HF-2018	44.43181° N, 73.20507° W	Adams and Windsor loamy sands	Somewhat excessively drained	71	2.1
IT-2018	44.49918°, N 73.20767° W	Winooski very fine sandy loam	Moderately well drained	36	2.8
MFF-2017	42.95159° N, 73.18287° W	Stockbridge loam	Well drained	304	3.6
OHS-2018	44.50189° N 73.21510° W	Winooski very fine sandy loam	Moderately well drained	36	3
SCF-2017	43.76931° N, 73.34058° W	Vergennes clay	Moderately well drained	121	5.8
SCF-2017	43.76931° N, 73.34058° W	Vergennes clay	Moderately well drained	121	5.8

2.4.2 Cultural practices

Two commonly planted legume cover crop mixes were selected for this research: field peas (*Pisum sativum*, var. ‘4010’) and oats (*Avena sativa*, var. ‘Kayouga’) in spring and hairy vetch (*Vicia villosa*) plus winter rye (*Secale cereale*) in fall. Certified organic seed and inoculant was purchased from Lakeview Organic Grain in Penn Yan, New York. Between 0.08 to 0.2 hectare plots were prepared at each farm site with a disc harrow prior to seeding the research plots. The cover crops were seeded at standard regional rates of 110 kg/ ha peas; 20 kg/ ha oats; 90 kg/ ha rye; 20 kg/ ha vetch. Pea and vetch seeds were inoculated with *Rhizobium leguminosarum* prior to planting (Parr et al., 2011). No irrigation was used throughout the course of the study. Seed drills that were locally available at each site were calibrated to the above seeding rate for plot establishment. During cover crop establishment and growth, the treatments with bare soil were managed with light tillage and hand hoeing to reduce interference from weeds. All other plots were weeded regularly with hoeing.

2.4.3 Cover crop termination and corn planting

Cover crops were terminated at one-week intervals beginning June 5-9 in 2017 and 2018. Since I was the only researcher conducting this study at multiple locations, each field activity took place over the course of several days. Cover crops were incorporated using a rototiller since this equipment was common to all farm sites. Cover crops were tilled with two passes for full residue burial. During the final cover crop incorporation, all blocks (including control and fertilized blocks) were tilled a final time in preparation for cash crop planting.

2.4.4 Experimental design

Plots were laid out with replicated randomized complete block design with five treatments and three replicates. Plot and block dimensions varied based on field shape, bed size, and farmer preference, but all plots had 3-meter buffer strips between blocks. Treatments are described in Table 2.

Table 2: Description of treatments for replicated blocks.

Treatment name	***Treatment description***	***Treatment fertilizer applications***
(A) Control	No cover crop	No N fertilizer. Fertilized with P and K to meet site specific soil test recommendations.
(B) Early incorporation	Incorporated 20-25 days before transplanting corn	No N fertilizer. Fertilized with P and K to meet site specific soil test recommendations.
(C) Mid incorporation	Incorporated 13-18 days before transplanting corn	No N fertilizer. Fertilized with P and K to meet site specific soil test recommendations.
(D) Late incorporation	Incorporated 6-11 days before planting corn	No N fertilizer. Fertilized with P and K to meet site specific soil test recommendations.
(E) Fertilizer	No cover crop.	Fertilized with standard rates of 5-4-3 fertilizer (equivalent to 112 N/ ha) and P and K to meet site specific soil test recommendations.

All plots were fertilized to meet the phosphorus and potassium recommendations based on standard soil test recommendations with North Country organic bone char (0-16-0) and potassium sulfate (0-0-52) prior to sweet corn planting. Controls were maintained weed free with light surface tillage and manual hoeing. Sweet corn, variety Montauk (81 days to maturity, Johnny's Selected Seeds, Winslow, ME) was seeded in 150 cell trays with two seeds per cell in a greenhouse into certified organic Vermont Compost Fort Vee potting soil. Sweet corn was transplanted in each plot seven to ten days following cover crop incorporation with transplant plugs (two corn plants per plug) spaced 60 cm apart in row with row spacing 90 cm apart for a plant density of 37,037 plants/ ha. A summary of the field activities is presented in Table 3.

Table 3: Summary of field activities and equipment used for farm sites.

Site-Year	Cover crop	CC seeding method	Treatment dimensions (m)	CC seeding	CC incorp (1,2,3)	Fertilize	Sweet corn transplant	Sweet corn harvest
CBF-2017	Oat-pea	1.8m Great plains no till drill 606NT	15.2x5.4	2017-04-22	6/3, 6/13, 6/23	2017-06-23	2017-06-28	2017-09-25
CBF-2018	Oat-pea	1.8m Great plains no till drill 606NT	15.2x5.4	2018-04-25	6/4, 6/14, 6/24	2017-06-24	2018-06-26	2018-09-01
CBF-2018	Rye-vetch	1.8m Great plains no till drill 606NT	15.2x5.4	2017-09-14	5/29, 6/4, 6/14	2017-06-14	2018-06-26	2018-09-01
GF-2017	Oat-pea	Carter small plot cone seeder	7.6x5.4	2017-04-20	6/5, 6/15, 6/25	2017-06-25	2017-06-30	2017-09-15
HF-2018	Oat-pea	3m Case IH	15.2x5.4	2018-05-02	6/2, 6/12, 6/22	2017-06-22	2018-06-28	2018-09-04
IT-2018	Oat-pea	3.6m Case IH 5100 with press wheels	15.2x5.4	2018-04-25	6/3, 6/13, 6/23	2018-06-23	2018-07-06	2018-08-30
IT-2018	Rye-vetch	3.6m Case IH 5100 with press wheels	15.2x5.4	2017-09-12	5/22, 6/5, 6/19	2018-06-19	2018-07-06	2018-08-30
MFF-2017	Oat-pea	1.8m Great plains no till drill 606NT	18.3x5.4	2017-04-24	6/3, 6/13, 6/23	2017-06-23	NA	NA
OHS-2018	Oat-pea	3.6m Case IH 5100 with press wheels	7.6x5.4	2018-04-25	5/22, 6/5, 6/19	2018-06-19	2018-07-06	2018-09-10
SCF-2017	Oat-pea	Carter small plot cone seeder	7.6x5.4	2017-04-25	6/6, 6/16, 6/26	2017-06-26	2017-07-05	2017-10-02
SCF-2018	Oat-pea	broadcast (spinner)	7.6x5.4	2018-04-30	6/4, 6/14, 6/24	2018-06-24	2018-06-29	2018-09-07
SCF-2018	Rye-vetch	broadcast (spinner)	7.6x5.4	2017-09-20	5/22, 6/5, 6/19	2017-06-19	2017-07-05	2017-10-02

2.4.5 Data collection

The soil nitrate test (Magdoff, 1991; Heckman, 2002) was used to measure the total amount of nitrate available for crops in the soil at the time of sampling. Samples were taken five to six times from each plot during each growing season to monitor changes in soil nitrate levels, as incorporated cover crops were breaking down and releasing nitrogen in the soil (Sullivan and Andrews, 2012). The first three sets of soil samples were analyzed for ammonium (NH^4+) as well as NO^3-N, but initial data suggested that NH^4-N was quickly nitrified and NO^3-N samples were sufficient (J. R. Heckman, 2002). Soils were sampled at a depth of 20-30 cm, packed in cloth bags and transported in a cooler to the UVM AETL immediately after sampling (Morris, 1998). UVM AETL uses the following for PSNT analysis: extract with 2 M KCl and use flow injection autoanalyzer (Lachat QuickChem method no. 12-107-06-2-A, Zellweger Analytics, Inc., Milwaukee, WI; Lachat Instruments, 1986) (Evanylo et al., 2008).

The total amount of nitrogen and carbon accumulated by legume cover crops was measured by harvesting samples of above-ground biomass in a 0.6 x 0.6 meter plot at termination, drying and weighing the samples (Gaskin et. al, 2022). This was accomplished by using a 0.6 x 0.6 m U-shaped quadrat assembled from PVC pipe. The material was harvested with a machete, packed into a 0.3 x 0.6 m cloth bag, and delivered to a drying room at the University of Vermont Horticultural Research and Education Center (HREC) in South Burlington, VT, at a temperature of 40° C for at least 48 hours. Samples were ground in a Wiley mill and analyzed for dry matter weight, percent nitrogen and percent carbon at the UVM AETL. At the time of sampling, the height of the cover crop was recorded.

Precipitation data were downloaded in the fall of 2018 and again for data verification in September of 2023 from the closest weather station to each site through the National Centers for Environmental Information, through the National Oceanic and Atmospheric Administration (https://www.noaa.gov/). Table 4 summarizes precipitation data and compares percent deviation from averages for the 2017 and 2018 seasons from two weather stations (Burlington and Rutland) in closest proximity to research sites. Growing degree day information[1] (GDD) was downloaded from weather stations in Bennington, Middlebury, and Burlington through Climate Smart Farming, a program of

[1] GDD = (Tmax-Tmix)/2 – Tbase, where Tmax is maximum daily temperature, Tmin is minimum daily temperature, and T base is set at 10 degrees C.

Cornell University (http://climatesmartfarming.org/). Figure 1 summarizes cumulative growing degree days for each site for 2017 and 2018.

Table 4: Seasonal precipitation data, 2017 & 2018

Burlington International Airport, VT*	**April**	**May**	**June**	**July**	**Aug**	**Sept**
Avg Precipitation	2.82	3.45	3.69	4.16	3.91	3.64
2017 Precipitation	3.83	4.91	7.17	3.45	2.40	2.79
% Deviation	36%	42%	94%	-17%	-39%	-23%
2018 Precipitation	4.84	1.98	4.1	2.52	2.54	4.2
% Deviation from average	72%	-43%	11%	-39%	-35%	15%
Rutland, VT*						
Avg Precipitation	2.88	3.7	3.97	4.76	4.07	3.71
2017 Precipitation	2.87	5.79	4.17	3.37	2.45	2.35
% Deviation	0%	56%	5%	-29%	-40%	-37%
2018 Precipitation	3.78	1.28	3.77	4.36	5.15	2.96
% Deviation from average	31%	-65%	-5%	-8%	27%	-20%

*National Weather Service data (https://www.ncei.noaa.gov/.)

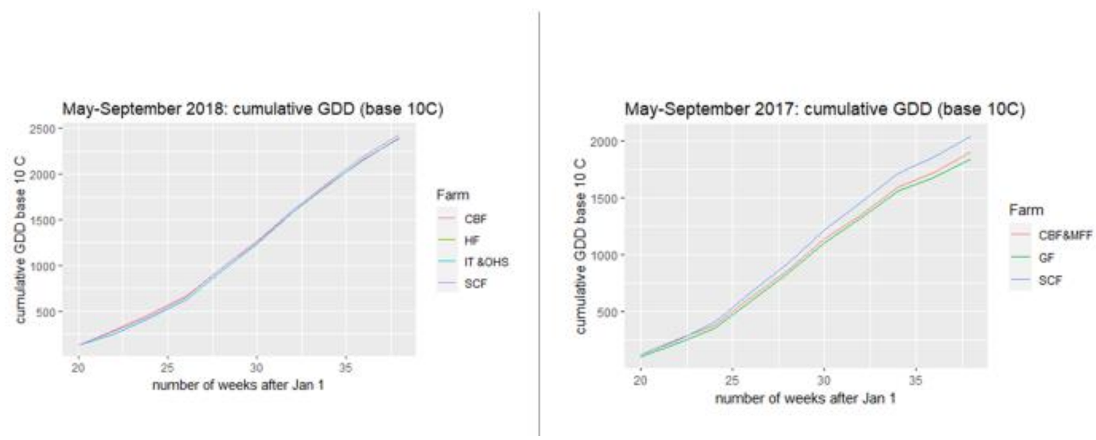

Figure 1: Cumulative Growing degree days (GDD) throughout the growing season. Data from National Weather Service.

2.5 Statistical Analysis

Data analysis was conducted using the statistical programming language "R" (R Core Team (2022)) to examine the significance of each factor on NO^3-N levels in the soil. One-way ANOVA was used to understand the effects treatment, precipitation, growing degree days, site year, and cover crop species had on soil nitrate levels, using Fisher's LSD as a post-hoc test. The ANOVA was then used to compare relationships between sweet corn yield, cover crop type treatment and biomass kg/ ha, treatment, and cover crop.

2.6 Results

2.6.1 Weather

Total accumulated growing degree days (GDD, base 10° C) and precipitation were each run as factors in one-way ANOVA with soil NO^3-N as the dependent variable. GDD had a highly significant effect on weekly mean soil NO^3-N (p= 0.0292). Precipitation did not have a significant effect on weekly mean nitrate, although there are clear trends by site year that demonstrate a decline in NO^3-N following heavy precipitation events.

Table 5: ANOVA analysis examining effects of factors on soil NO^3-N across all site years. Weekly mean NO^3-N was used to analyze precipitation and GDD.

Factor	***F-statistic***	***P-Value***
Treatment	5.945	0.000103***
Precipitation	0.153	0.696
GDD	912.5	0.0292*
Site Year	71.18	<2e-16 ***
CC species	6.225	0.013 *
Biomass (kgN/ha)	0.864	0.355
Soil type	51.97	<2e-16 ***
Week number	8.4111	5.3e-11 ***

2.6.2 Effect of treatment on quantity of NO^3-N release

There was a significant difference (see Table 5) between treatment and soil NO^3-N levels. Using Fisher's least significant difference (LSD) as a post-hoc test, the fertilizer treatment stood out with the highest NO^3-N. Using a filter to test just the effect of three cover crop incorporation times on NO^3-N did not demonstrate significance (p=0.07) but showed a clear trend of higher NO^3-N levels from the early incorporation.

2.6.3 Timing of NO^3-N release

To understand if the release of the NO^3-N synchronized with cash crop uptake, the effect of week number on NO^3-N was examined using with one-way ANOVA tests. Using Fisher's LSD, week numbers were sorted by order of significance. Week number 28 (after Jan 1) demonstrated the highest level of NO^3-N across all site years and for all treatments. The "dyplr" Wickham et al., 2022) function in R-studio was used to filter by week number, then ANOVA was applied to test treatment effects on NO^3-N at week number 28. This revealed the effect of treatment on soil NO^3-N at 28 weeks is highly significant (p=0.00481). Table 6 shows NO^3-N levels across all site years at week 28 and standard deviation using Fisher's LSD. The fertilizer treatment demonstrated the highest level of soil nitrate at week 28. When examining the timing of release from cover crop treatments only, there was a significant difference between the two cover crop types, with oat-pea peaking at week 26 and rye-vetch at week 28 (table 6). There were high standard deviations for all treatments.

Table 6: Effect of treatment across all site years on NO^3-N levels and standard deviation at 28 weeks after Jan 1. Calculated using Fisher's LSD.

Treatment	*NO^3-N at 28 weeks*	*sd*
control	20.11768	13.418679
early	20.99833	11.596746
fertilizer	27.00984	15.634306
late	16.01404	7.561573
mid	16.78.589	9.052093

2.6.4 Effect of cover crop type on nitrate

There were eight total plantings of oat-pea cover crops seeded in spring of 2017 and 2018 and three rye-vetch cover crops, seeded in fall 2017 and incorporated in spring 2018. Cover crop type had a significant effect on soil nitrate with a P-value of 0.013 (Table 5). Using Fisher's LSD, Rye-Vetch had a mean NO^3-N of 18.01533 (+/- 14.39); Oat-Pea 14.69700 (+/- 9.35). Rye-Vetch NO^3-N peaked at week 28; Oat-Pea peaked at week 26 (see Figure 2). There was a high variability across all week numbers.

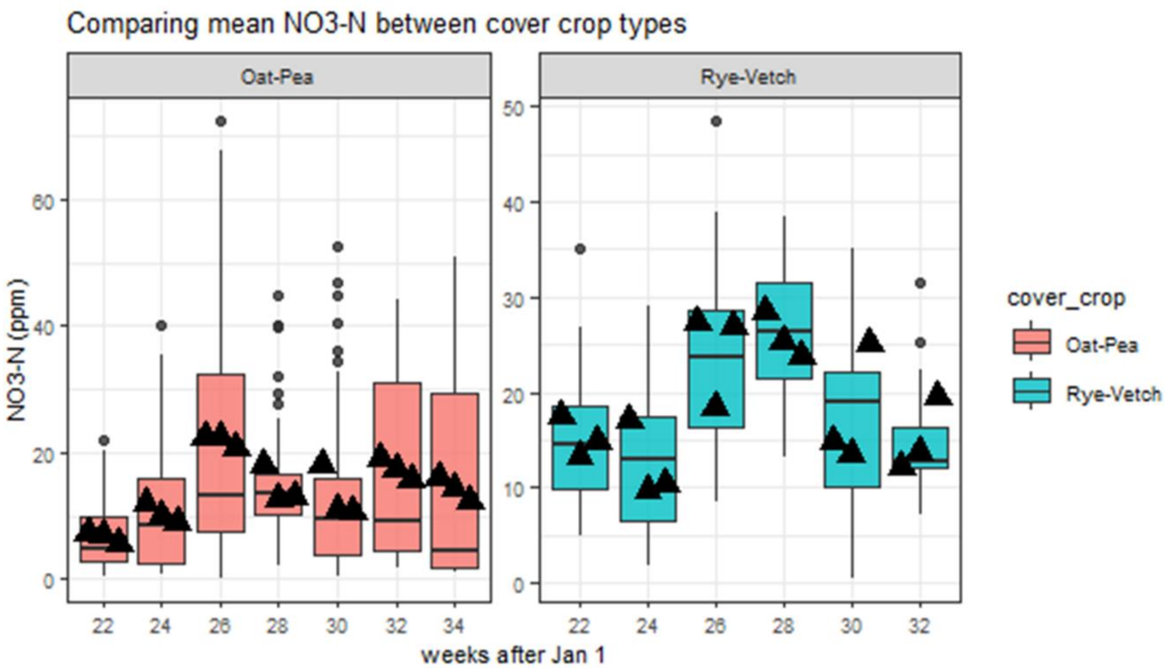

Figure 2: Comparison of Oat-Pea and Rye-Vetch cover crops on mean soil NO^3 levels over time (weeks after Jan 1).

2.6.5 Biomass accumulation per cover crop

Biomass (kg N/ha) was significantly different between oat-pea and rye-vetch treatments. Cover crop biomass ranged from 13-38 kg N/ ha-1 for oat-pea and 9.4-77 kg N/ ha-1 for rye vetch. There was also differences in the C:N ratio between the two cover crops. Spring seeded peas and oats had a low C:N ratio at incorporation time, ranging from 9.3-22.9. In contrast, over-wintered rye-vetch had more biomass and higher C:N ratio, ranging from 15.5-29.5 in this study. The higher C:N in rye vetch plots led to slower mineralization. While there is no significant overall relationship between biomass and NO^3-N, the data show a trend in later peak release (week 28-30) of NO^3-N from rye-vetch, and a longer duration of availability in comparison to oat-pea.

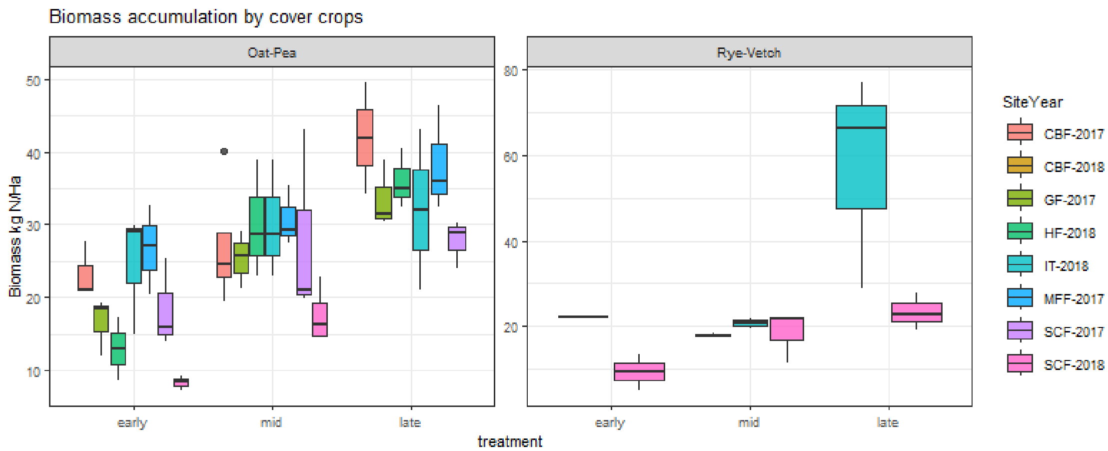

Figure 3: Biomass accumulation by cover crops measured in kg N/ha-1 across different treatment times.

2.6.6 Soil type and site year

Several soil types were represented in this study, ranging from loamy sand to clay. Soil organic matter levels were 2% at the sandiest site and 10% on the clay. Each site had different management histories and residual fertility (see Table 1). In the statistical analysis, soil type was a very significant factor in soil nitrate levels (p=<2e-16). Soil organic matter percent and site year are closely linked to soil type in this study and had the same p-value as soil type in a one-way ANOVA. Therefore, soil organic matter and site year also demonstrated a highly significant impact (p=<2e-16) on soil NO^3-N levels. Figure 4 shows high variation of soil NO^3-N data across all farm site years.

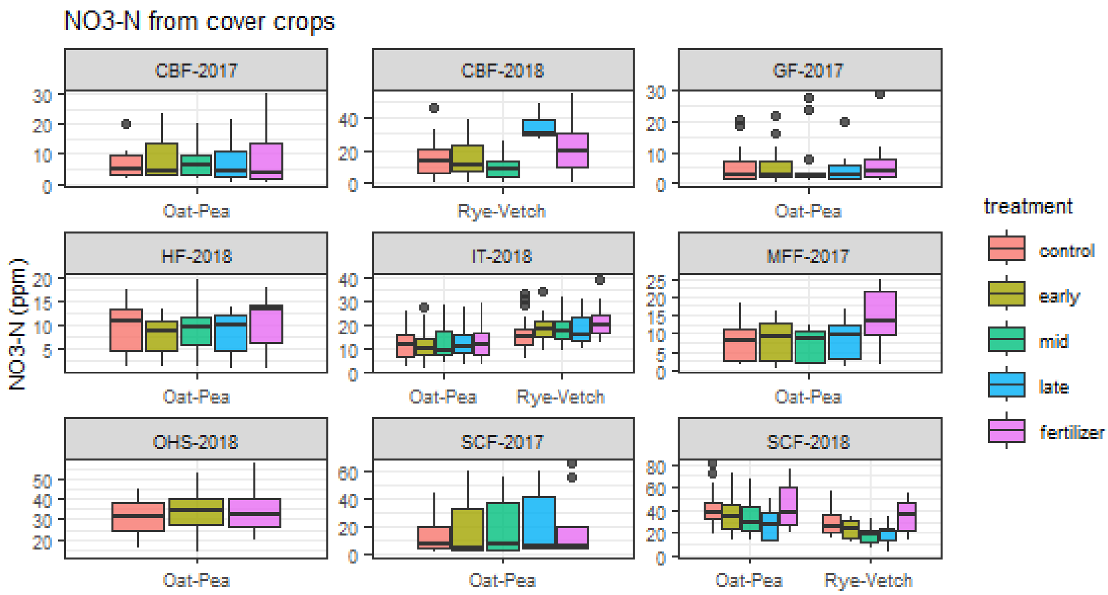

Figure 4: NO3-N across entire sampling period for each site year by treatment.

Analyzing each farm site individually revealed site-specific trends in soil nitrate availability. Figure 5 shows soil NO^3-N at one site ("CBF"). The data reflects combined soil nitrate samples from 2017&2018 for oat-pea and 2018 data for rye-vetch.

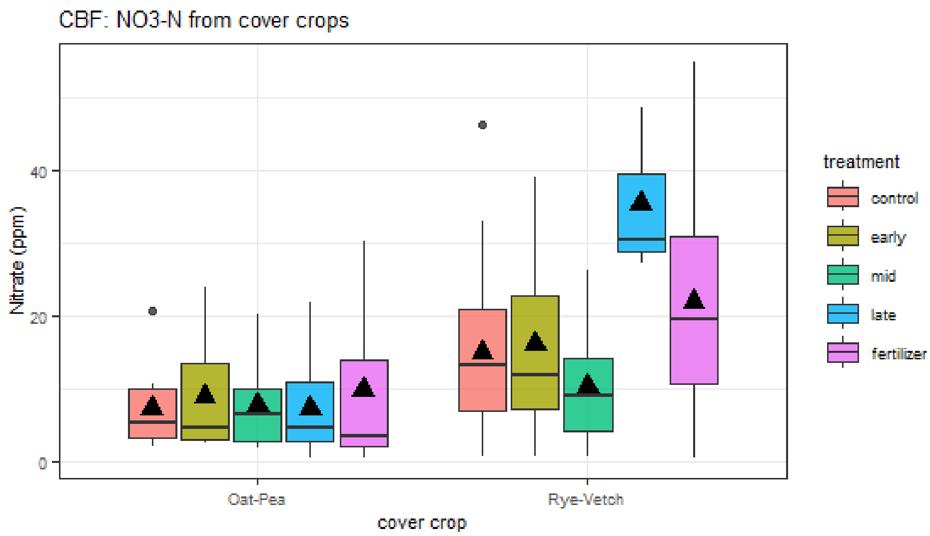

Figure 5: NO^3-N from oat-pea (2017&2018) and rye-vetch (2018) cover crops at one farm site.

2.6.7 Sweet corn yield

Sweet corn yield was affected by treatment (p=0.05). Fertilizer had the most significant impact on yield with an average of 23.8 ears from 30 plants, with SD +/- 12.8 (figure 6). The number of marketable ears showed a correlation with the fertilizer treatment. The data also demonstrated trends towards increased yields based on the late incorporation date. Yield for several site years was destroyed due to pest issues. Yield was not significantly related to soil NO^3-N levels, biomass, site-year, precipitation, or growing degree days. Figure 6 shows the relationship between treatment and marketable yield for each site year.

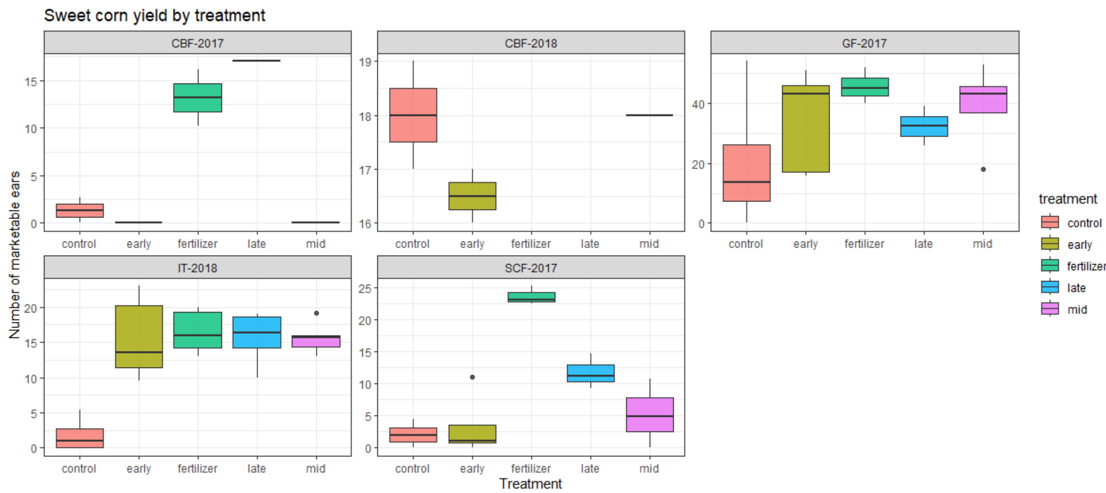

Figure 6: Marketable sweet corn yield based by treatment, representing each site year successfully harvested.

2.7 Discussion

2.7.1 Quantity of NO^3-N from legume cover crops

This study showed that it is possible for legume cover crops grown on Vermont vegetable farms to provide sufficient N to meet cash crop needs if aligned with uptake, but that the quantity and timing of plant available N is highly context dependent and not simple to predict. The statistical analyses performed here revealed the limitations of quantifying legume cover crop N based on incorporation time, as is demonstrated by the lack of significance from results of ANOVA analysis of early, mid, and late cover crop treatments across all sites. What is revealed in this analysis is a connection between the amount of biomass produced by the cover crop, subsequent soil nitrate levels, and sweet corn yield. This study also demonstrated the significant impact temperature has on soil nitrate mineralization, indicated by growing degree days. Finally, these results highlight the importance of accounting for site specific factors such as soil type and soil organic matter levels. In future efforts to understand the utility of legume cover crops on vegetable farms, a high emphasis should be placed on the factors we found significant, including soil type, week number, cover crop type, biomass accumulated, and growing degree days.

Only 20% of all PSNT samples in this study were above the "sufficiency" threshold (>25 ppm) for vegetable crops, which means that during the rapid cash crop growth phase, there would be no additional sidedress recommended (J. R. Heckman, 2002). Accordingly, the remaining 80% of the samples demonstrated inadequate soil N (<25 ppm) for optimal sweet corn crop production (J. R. Heckman, 2002).

2.7.2 Effect of background fertility and biological legume N fixation

Organic N is constantly mineralizing and immobilizing throughout the season, governed by background and residual soil fertility, temperature, moisture, soil biology, plant roots, and farm practices (Stute & Posner, 1995; Wienhold & Halvorson, 1999). Prior to cover crop establishment, the pools of organic N in this study varied widely from site to site and year to year, determined by soil characteristics (SOM and soil type), background fertility (e.g., previous years composts, manure, cover crops or amendments), precipitation, and temperature (GDD).

Some studies show that background levels of soil nitrate can inhibit biological N fixation and subsequent nodulation of legume cover crops (Perrone et al., 2020; Voisin et al., 2002). This means that for site-years with high levels of background fertility, the legume cover crops may not have fixed any atmospheric nitrogen; instead, they took up nitrate already available in the soil, and released it again once incorporated. Research by

Voisin et al. shows an absolute inhibition of biological fixation by legumes at soil nitrate levels above 84 ppm and reduced fixation starting at 12.5 ppm NO^3-N (Voisin et al., 2002). The authors demonstrated that the percent N fixed by legumes could be predicted as a linear function of mineral N in the top 30 cm of soil, demonstrating that soil mineral N has a quantitative limitation on amount of N fixed by legume cover crops. The authors also noted that this relationship is affected by soil type, specifically clay content, which determines the amount of N that can be mineralized from the SOM (Voisin et al., 2002). The paper supports the findings from this research, particularly on farms that had high SOM and residual fertility (OH, SCF). These sites showed a perplexingly high level of NO^3-N from the control sites and no significant impact of the legume cover crop on NO^3-N availability after incorporation. Instead, the cover crops acted as a temporary "sink" for the soil available N, reducing the NO^3-N levels in the treatments below the control and fertilized plots prior to incorporation. After incorporation, the cover crop treatments rebounded back to the same range of NO^3-N as the control plots, which suggests that the cover crops took up NO^3-N from the soil and released it upon incorporation. The fertilized plots were the only treatments for these sites that showed significantly higher NO^3-N levels. These findings imply that prior to deciding to plant a legume cover crop, farmers should estimate potential N contributions from background fertility and SOM (Perrone et al., 2020) because there is likely no N-fixing contribution from legumes on sites with high mineral N.

2.7.3 Alignment with cash crop N needs

In order to maximize the benefits of utilizing legume N, there must be synchrony between NO^3-N release and cash crop uptake (Stute & Posner, 1995). Although vegetable crops vary in the timing of this, it is typically in a rapid growth, or "second growth phase" (J. R. Heckman, 2002). Farmers anticipate this period of uptake by understanding the growth patterns of specific crops; for sweet corn in Vermont, typical sidedress timing is when plants are in the "V6" stage (6^{th} collared leaf) (Sullivan et al., 2020) or when the plants are 6-10" tall (B. Sideman et al., 2023). This stage usually occurs 30 days after seeding sweet corn (Sullivan et al., 2020). In this study, the corn was seeded approximately 21-28 days before maximum NO^3-N availability. In this case, the rapid growth phase of sweet corn occurred slightly ahead of maximum NO^3-N availability, but fairly-well synchronized. The data revealed a differential trend between cover crop types, with the earlier release from oat-pea aligning better with cash crop needs than rye-vetch. The data also showed that the mineralization rates of soil mineral N, fertilizer N, and cover crop N occur at similar rates, peaking at similar times.

2.7.4 Comparing cover crops

Based on the biomass samples collected in our study, the potential N contribution of oat-pea cover crops ranged from 13-38 kg N/ ha and for rye-vetch, 9.4-77 kg N/ ha. 20% of the PSNT samples had higher NO^3-N than even the highest biomass N contribution accounts for, confirming that additional N mineralized from soil organic matter and residual fertility. The C:N ratio of the two cover crops is a good predictor of timing of NO^3-N availability after cover crop incorporation (Finney et al., 2016; Perrone et al., 2020). Existing literature suggests that if cover crop biomass has a C:N ratio above 30, there is a predictable N tie up while the cover crop is broken down; if the ratio is less than 20, release of N is likely. If the C:N ratio is between 20 and 30, N is not likely to be mineralized or tied up (Finney et al., 2016). This study showed a significant difference in the C:N ratio between the two cover crops: only 8% of the oat-pea plots samples had a C:N>20:1, whereas 40% of the rye-vetch samples had C:N >20:1. In both of the cover crop mixes, biomass samples >20:1 were from the "late" incorporation date, suggesting that an earlier incorporation time would reduce the C:N ratio and accelerate subsequent NO^3-N availability.

2.7.5 Utility of PSNTs

Several studies have shown that taking a PSNT during a several day window previous to the cash crop rapid growth phase will help farmers decide if they need additional fertilizer N and how much they should apply for optimum yield (Hartz et al., 2000; Hartz, 2006; Heckman, 2002; Sideman et al., 2023). Building from this knowledge, it seems logical that the PSNT would also be a useful tool to understand how much NO^3-N is available for cash crop use following legume cover crop incorporation. Having a reliable way for vegetable growers to measure available N after legume cover crops would remove uncertainty and increase farmer adoption of legume cover crops as a source of N (Radicetti et al., 2017). Ideally, the PSNT could guide farmers in fertility decisions following legume cover crop incorporation, leading to improved yields and/or reduced overapplications of N fertilizer (Hartz, 2006; Kaye & Quemada, 2017).

However, the PSNT has been shown to have limited applicability on different soil types. The PSNT is recommended for use on loamy soils but not on sand or heavy clay (Heckman, 2002; Laboksi & Peters, 2012). Furthermore, researchers have found that the PSNT overestimates sidedress recommendations if spring temperatures are cool, and underestimates when spring temperatures are warm (Laboksi & Peters, 2012). Recommendations also note that farmers using the PSNT should deduct residual fertility from previous years' manure or legume applications to calculate sidedress rates (Laboksi & Peters, 2012). However, none of these nuances are explicitly presented to most farmers when they receive PSNT results from the soil lab; the farmer simply receives sidedress recommendations based on the ppm NO^3-N. If a farm scenario is outside of the scope of PSNT effectiveness–for example, clay soils or high background fertility—following PSNT recommendations may lead to unexpected or even negative outcomes.

This research showed that there is little reliable information to be gained from the PSNT when used to predict cash crop outcomes on a range of vegetable farms in Vermont. Periodic PSNTs do not accurately reflect the complex dynamics, biologically driven nutrient cycling in the soil (Grandy et al., 2022). This is exemplified at one of the farm sites, which had the highest yield of sweet corn but low soil nitrate levels on all treatments for each sampling period. Information from the PSNTs would have suggested that the farmer had to sidedress N, yet the yield data from this site suggested a highly efficient NO^3-N utilization. This farm's soil is a sandy loam, and as noted by Heckman (2002), PSNTs on sandy soils may not offer much guidance because they are almost always low in NO^3-N. Given the high yields at this site, these findings suggest that the cover crops and fertilizer both provided NO3-N that was quickly utilized by the crops and not captured in PSNT results. At this site, sweet corn yield was statistically significant based on treatment effect, which aligned with study expectations that the highest yield would be from the fertilized treatment, next highest yield would be from the late cover crop incorporation, and virtually no yield from the control.

Conversely, another site had high amounts of NO^3-N measured on PSNTs during peak cash crop uptake which indicates more than sufficient plant available N. This site has Vergennes clay soil type and stands out for extremely high soil nitrate levels for all treatments during all sampling periods. As discussed previously, high SOM (10%) and residual fertility on this site accounted for a high rate of NO^3-N mineralized from the soil and likely inhibited biological N fixation of the legumes (Voisin et al., 2002). This offers an explanation for higher NO^3-N levels in control and fertilized plots during the period of cover crop growth, which was absorbing rather than fixing NO^3-N. The high NO^3-N in all treatments may also be partially related to ammonium (NH4+) held in exchange sites on clay soil particles. This unique "fixation" and "defixation" of ammonium to nitrate is thought to only occur in clay soils and is related to a complex dynamic with other cations (Nieder et al., 2011). However, despite high PSNT results during the rapid growth phase of the sweet corn, the cash crop showed minimal uptake and the cash crop performance was poor. Plants were visually nitrogen deficient in all treatments and yield was low in all plots except the fertilized treatments.

Heckman et al. (1995) conducted a similar study using the PSNT to calibrate the response of sweet corn to varying rates of manure application on farms with many different microclimates and soil types sites across New Jersey. The conclusions from Heckman et al. (1995) align with this study, for they found a poor correlation between soil NO^3-N and yield when PSNT was below critical soil test levels. They conclude that in these cases, the PSNT is not useful in predicting yield. The authors conclude that the lack of accuracy is because of unequal rates of N mineralization due to different soil types and conditions (Heckman et al., 1995). Other papers have also demonstrated that without contextual information, following PSNT recommendations does not result in higher yields (Clark et al., 2020).

This research suggests that while there can be direct correlations between legume cover crop incorporation and cash crop yield, the PSNT is not a reliable predictive tool of this relationship. It also more broadly calls into question the value of using any fixed measure like the PSNT to offer management recommendations for vegetable farms without accounting for a wide spectrum of context specific variables, such as soil type, background fertility, and GDD. However, since farmers have the knowledge and ability to interpret recommendations for their own situation, one outcome of this research may be to develop more nuanced guidance for farmers to better utilize the PSNT by integrating factors such as temperature, soil texture, organic matter, residual fertility, etc. into a model of N availability predictions.

2.7.6 Benefits and challenges to conducting on farm research

In the original conception of this project, the farmers would establish and maintain research plots that were integrated into their sweet corn production fields. It quickly became apparent that replicated blocks are time intensive for farmers to manage and incompatible with their mechanized systems. The trial was complicated by changes at two farm sites: one farm changed cash crops at planting time which resulted in no yield data, another accidentally disced the entire research plot, leaving only one incorporation treatment, and another farm leased the nicely cover cropped plot to a CBD farmer.

Sweet corn was selected for this research because it was a crop all participant farms grew commercially, the timing fit into the study, and it is an easy crop to collect yield data from. However, one of the biggest data losses in this project was wildlife damage to sweet corn yield. Three of the site years had 100% loss to racoons, leaving no yield data. There was minor damage from birds on several other sites. Since sweet corn is particularly attractive to multiple herbivores, fall cabbage may be a more reliable choice for yield data for future research.

There are many positive and lasting impacts resulting from this on-farm research. Conducting this study on a diversity of farm sites led to conclusions that would not have resulted from a single controlled research site. The differences across farms and wide range of results from the study resulted in confounding data, but also prompted deeper examination of the interdependence of agroecological systems. This research affirms the dynamic nature of nutrient cycles and the influence that soil type, biology, climate, and practices all exert on it. This research also helped build lasting relationships with partner farms. These farms have stayed in close contact since the study, and several have participated in other projects (including the high tunnel tomato project in Chapter Three and the soil health interviews in Chapter Four of this dissertation). An unforeseen outcome of this study is that participating farms have reduced their reliance on P based fertilizers and increased their use of legume cover crops. The adoption of these practices has had a ripple effect in the vegetable community in Vermont, and as discussed in Chapter 4 of this dissertation, other farmers are learning from this and experimenting with adjusted inputs and more cover crops.

2.8 Conclusion

Approximately 1000 samples were taken for this project with the intent of capturing a pattern of legume N availability across farms with varying soils and practices. Extensive efforts were made to analyze the data for significance related to incorporation time and plant available nitrogen. This data varied widely and was highly influenced by site, soil, climate, and farm practices. The real story told by this data involves the context-specific nature of cover crop N mineralization and the many complex factors that influence the quantity and release rate of this highly mobile, biologically mediated nutrient. Moreover, these data emphasize the need for future examination of the use of some of our common tests which may prove to be misleading or harmful depending upon the context.

The original intention of this research was to help farmers reduce reliance on fertilizer-N sources that are also high in phosphorus by providing clear guidance on the availability of N following legume cover crops. However, the findings from this two-year study led to other uncertainties, or, looked at in another way, point towards a more nimble, ecologically complex approach to understanding N availability. Many of the cited studies examining legume cover crop N and the use of the PSNT were done on conventional farms with predictable nitrogen and crop dynamics, a high dependency on inorganic N, and quantifiable yield outcomes. In contrast, this study took place on diversified organic farms that are focused on ecological soil health practices. Grandy et al. (2022) argue that farms with complex soil health require a more holistic approach to understanding N availability as understandings of soil N shift away from a linear predictability and towards a more cyclic understanding (Grandy et al., 2022). Soils with a diverse ecology, such as those included in this study, support multiple potential sources of bioavailable N. For example, emerging work by Jilling et al. (2018) reveals that pools of N previously dismissed as unavailable to plants known as mineral-associated organic matter (MAOM) are potentially significant sources of bioavailable N.

Data from this study will be useful to help Vermont vegetable farmers, especially organic farmers, anticipate the timing of N availability from all pools of organic N. Although it is disappointing that evidence did not support that legume N was a reliable source of N in this research, these results offer promising guidance to Vermont growers: if they account for all potential sources of N in the soil, peak plant available N can be predicted between weeks 26-28 of the calendar year, at approximately 680 GDD (mid to late June). This study highlights the importance of integrating farmer knowledge about site specific factors such as background fertility and soil organic matter, to help inform variables and better predict legume cover crop N potential. These conclusions point towards a collaborative approach to soil fertility, using farmer-informed guidance to better understand how much N farmers can expect from legume cover crops.

2.9 References

Aare, A. K., Lund, S., & Hauggaard-Nielsen, H. (2021). Exploring transitions towards sustainable farming practices through participatory research – The case of Danish farmers' use of species mixtures. *Agricultural Systems*, *189*, 103053. https://doi.org/10.1016/j.agsy.2021.103053

Blevins, R. L., Herbek, J. H., & Frye, W. W. (1990). Legume Cover Crops as a Nitrogen Source for No-Till Corn and Grain Sorghum. *Agronomy Journal*, *82*(4), 769–772. https://doi.org/10.2134/agronj1990.00021962008200040023x

Clark, J. D., Fernández, F. G., Veum, K. S., Camberato, J. J., Carter, P. R., Ferguson, R. B., Franzen, D. W., Kaiser, D. E., Kitchen, N. R., Laboski, C. A. M., Nafziger, E. D., Rosen, C. J., Sawyer, J. E., & Shanahan, J. F. (2020). Adjusting corn nitrogen management by including a mineralizable-nitrogen test with the preplant and presidedress nitrate tests. *Agronomy Journal*, *112*(4), 3050–3064. https://doi.org/10.1002/agj2.20228

Coleman, E. (2018). *The New Organic Grower*. Chelsea Green Publishing Pub.

Darby, H., Burke, C., Cummings, E., Harwood, H., Madden, R., & Monahan, S. (2012). Cover Crop Planting Date x Seeding Rate Trial. *Northwest Crops & Soils Program*. https://scholarworks.uvm.edu/nwcsp/37

Drinkwater, L. E., & Snapp, S. S. (2007). Nutrients in Agroecosystems: Rethinking the Management Paradigm. In D. L. Sparks (Ed.), *Advances in Agronomy* (Vol. 92, pp. 163–186). Academic Press. https://doi.org/10.1016/S0065-2113(04)92003-2

Evanylo, G., Sherony, C., Spargo, J., Starner, D., Brosius, M., & Haering, K. (2008). Soil and water environmental effects of fertilizer-, manure-, and compost-based fertility practices in an organic vegetable cropping system. *Agriculture, Ecosystems & Environment*, *127*(1), 50–58. https://doi.org/10.1016/j.agee.2008.02.014

Ferguson, B. J., Mens, C., Hastwell, A. H., Zhang, M., Su, H., Jones, C. H., Chu, X., & Gresshoff, P. M. (2019). Legume nodulation: The host controls the party. *Plant, Cell & Environment*, *42*(1), 41–51. https://doi.org/10.1111/pce.13348

Finney, D. M., White, C. M., & Kaye, J. P. (2016). Biomass Production and Carbon/Nitrogen Ratio Influence Ecosystem Services from Cover Crop Mixtures. *Agronomy Journal*, *108*(1), 39–52. https://doi.org/10.2134/agronj15.0182

Gaskell, M., & Smith, R. (2007). Nitrogen Sources for Organic Vegetable Crops. *HortTechnology Hortte*, *17*(4), 431–441. https://doi.org/10.21273/HORTTECH.17.4.431

Gaskin, J., Cabrera, M., & Kissel, D. (2016). *Predicting Nitrogen Release from Cover Crops: THE COVER CROP NITROGEN AVAILABILITY CALCULATOR*. University of Georgia Extension. https://Extension.uga.edu/publications/detail.html?number=B1466

Gaskin, J., Hancock, D., Uttam, S., & Chatam, K. (2022). Cover Crop Biomass Sampling. University of Georgia. Retrieved on August 3, 2023 from https://extension.uga.edu/publications/detail.html?number=C1077&title=cover-crop-biomass-sampling.

Gershuny, G., & Smillie, J. (1999, March 3). *The Soul of Soil—Chelsea Green Publishing*. https://www.chelseagreen.com/product/the-soul-of-soil/

Grandy, A. S., Daly, A. B., Bowles, T. M., Gaudin, A. C. M., Jilling, A., Leptin, A., McDaniel, M. D., Wade, J., & Waterhouse, H. (2022). The nitrogen gap in soil health concepts and fertility measurements. *Soil Biology and Biochemistry*, *175*, 108856. https://doi.org/10.1016/j.soilbio.2022.108856

Griffin, G., Jokela, W., Ross, D., Pettinelli, D., Morris, T., & Wolf, A. (2011). *Recommended Soil Nitrate Tests*. *493*.

Hartz, T. K. (2006). Vegetable Production Best Management Practices to Minimize Nutrient Loss. *HortTechnology*, *16*(3), 398–403. https://doi.org/10.21273/HORTTECH.16.3.0398

Hartz, T. K., Bendixen, W. E., & Wierdsma, L. (2000). The Value of Presidedress Soil Nitrate Testing as a Nitrogen Management Tool in Irrigated Vegetable Production. *HortScience*, *35*(4), 651–656. https://doi.org/10.21273/HORTSCI.35.4.651

Heckman, J., Hlubik, W., Prostak, D. J., & Paterson, J. W. (1995). Pre-sidedress Soil Nitrate Test for Sweet Corn. *HortScience: A Publication of the American Society for Horticultural Science*, *30*. https://doi.org/10.21273/HORTSCI.30.5.1033

Heckman, J. R. (2002). In-season Soil Nitrate Testing as a Guide to Nitrogen Management for Annual Crops. *HortTechnology*, *12*(4), 706–710. https://doi.org/10.21273/HORTTECH.12.4.706

Heckman, J. R., Samulis, R., & Nitzsche, P. (2002). Sweet Corn Crop Nitrogen Status Evaluation by Stalk Testing. *HortScience*, *37*(5), 783–786. https://doi.org/10.21273/HORTSCI.37.5.783

Helling, A. P., Conner, D. S., Heiss, S. N., & Berlin, L. S. (2015). Economic Analysis of Climate Change Best Management Practices in Vermont Agriculture. *Agriculture*, *5*(3), Article 3. https://doi.org/10.3390/agriculture5030879

Horner, C. (2023). Exploring Potential Domains of Agroecological Transformation in the United States. *Graduate College Dissertations and Theses*. https://scholarworks.uvm.edu/graddis/1658

Jahanzad, E., Barker, A. V., Hashemi, M., Eaton, T., Sadeghpour, A., & Weis, S. A. (2016). Nitrogen Release Dynamics and Decomposition of Buried and Surface Cover Crop Residues. *Agronomy Journal*, *108*(4), 1735–1741. https://doi.org/10.2134/agronj2016.01.0001

Jilling, A., Keiluweit, M., Contosta, A. R., Frey, S., Schimel, J., Schnecker, J., Smith, R. G., Tiemann, L., & Grandy, A. S. (2018). Minerals in the rhizosphere: Overlooked mediators of soil nitrogen availability to plants and microbes. *Biogeochemistry*, *139*(2), 103–122. https://doi.org/10.1007/s10533-018-0459-5

Kaye, J. P., & Quemada, M. (2017). Using cover crops to mitigate and adapt to climate change. A review. *Agronomy for Sustainable Development*, *37*(1), 4. https://doi.org/10.1007/s13593-016-0410-x

Laboksi, C. A. M., & Peters, J. B. (2012). *Nutrient Application Guidelines for Field, Vegetable, and Fruit Crops in Wisconsin (A2809)*.

Lawson, A., Fortuna, A. M., Cogger, C., Bary, A., & Stubbs, T. (2013). Nitrogen contribution of rye–hairy vetch cover crop mixtures to organically grown sweet corn. *Renewable Agriculture and Food Systems*, *28*(1), 59–69. https://doi.org/10.1017/S1742170512000014

Liebman, A. M., Grossman, J., Brown, M., Wells, M. S., Reberg-Horton, S. C., & Shi, W. (2018). Legume Cover Crops and Tillage Impact Nitrogen Dynamics in Organic Corn Production. *Agronomy Journal*, *110*(3), 1046–1057. https://doi.org/10.2134/agronj2017.08.0474

Magdoff, F. (1991). Understanding the Magdoff Pre-Sidedress Nitrate Test for Corn. *Journal of Production Agriculture*, *4*(3), 297–305. https://doi.org/10.2134/jpa1991.0297

Mason, R. E., Merrill, S. C., Görres, J., Faulkner, J., & Niles, M. T. (2021). Agronomic and environmental performance of dairy farms in a warmer, wetter climate. *Journal of Soil and Water Conservation*, *76*(1), 76–88. https://doi.org/10.2489/jswc.2021.00169

Méndez, V. E., Caswell, M., Gliessman, S. R., & Cohen, R. (2017). Integrating Agroecology and Participatory Action Research (PAR): Lessons from Central America. *Sustainability*, *9*(5), Article 5. https://doi.org/10.3390/su9050705

Morris, T. (1998). Soil sample bag effects on pre-sidedress soil nitrate test concentrations. *Communications in Soil Science and Plant Analysis - COMMUN SOIL SCI PLANT ANAL*, *29*, 2529–2537. https://doi.org/10.1080/00103629809370130

Nieder, R., Benbi, D. K., & Scherer, H. W. (2011). Fixation and defixation of ammonium in soils: A review. *Biology and Fertility of Soils*, *47*(1), 1–14. https://doi.org/10.1007/s00374-010-0506-4

Parr, M., Grossman, J. M., Reberg-Horton, S. C., Brinton, C., & Crozier, C. (2011). Nitrogen Delivery from Legume Cover Crops in No-Till Organic Corn Production. *Agronomy Journal*, *103*(6), 1578–1590. https://doi.org/10.2134/agronj2011.0007

Perkus, E. A. (2018). *UNIVERSITY OF MINNESOTA*.

Perrone, S., Grossman, J., Liebman, A., Sooksa-nguan, T., & Gutknecht, J. (2020). Nitrogen fixation and productivity of winter annual legume cover crops in Upper Midwest organic cropping systems. *Nutrient Cycling in Agroecosystems*, *117*(1), 61–76. https://doi.org/10.1007/s10705-020-10055-z

Phosphorus Sources. (n.d.). Lake Champlain Basin Program. Retrieved November 13, 2022, from https://www.lcbp.org/our-goals/clean-water/nutrients-and-cyanobacteria/phosphorus-sources/

Poffenbarger, H. J., Mirsky, S. B., Weil, R. R., Kramer, M., Spargo, J. T., & Cavigelli, M. A. (2015). Legume Proportion, Poultry Litter, and Tillage Effects on Cover Crop Decomposition. *Agronomy Journal*, *107*(6), 2083–2096. https://doi.org/10.2134/agronj15.0065

Prasad, R., & Chakraborty, D. (2019). *Phosphorus Basics: Understanding Phosphorus Forms and Their Cycling in the Soil*. Alabama Cooperative Extension System. https://www.aces.edu/blog/topics/crop-production/understanding-phosphorus-forms-and-their-cycling-in-the-soil/

R Core Team (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Radicetti, E., Campiglia, E., Marucci, A., & Mancinelli, R. (2017). How winter cover crops and tillage intensities affect nitrogen availability in eggplant. *Nutrient Cycling in Agroecosystems*, *108*(2), 177–194. https://doi.org/10.1007/s10705-017-9849-7

Required Agricultural Practices | Agency of Agriculture Food and Markets. (n.d.). Retrieved August 4, 2022, from https://agriculture.vermont.gov/rap

Roques, S. E., Kindred, D. R., Berry, P., & Helliwell, J. (2022). Successful approaches for on-farm experimentation. *Field Crops Research*, *287*, 108651. https://doi.org/10.1016/j.fcr.2022.108651

Rosen, C. J., & Allan, D. L. (2007). Exploring the Benefits of Organic Nutrient Sources for Crop Production and Soil Quality. *HortTechnology*, *17*(4), 422–430. https://doi.org/10.21273/HORTTECH.17.4.422

Schattman, R. E., Méndez, V. E., Merrill, S. C., & Zia, A. (2018). Mixed methods approach to understanding farmer and agricultural advisor perceptions of climate change and adaptation in Vermont, United States. *Agroecology and Sustainable Food Systems*, *42*(2), 121–148. https://doi.org/10.1080/21683565.2017.1357667

Schipanski, M. E., Barbercheck, M., Douglas, M. R., Finney, D. M., Haider, K., Kaye, J. P., Kemanian, A. R., Mortensen, D. A., Ryan, M. R., Tooker, J., & White, C. (2014). A framework for evaluating ecosystem services provided by cover crops in agroecosystems. *Agricultural Systems*, *125*, 12–22. https://doi.org/10.1016/j.agsy.2013.11.004

Scholefield, D., & Titchen, N. m. (1995). Development of a rapid field test for soil mineral nitrogen and its application to grazed grassland. *Soil Use and Management*, *11*(1), 33–43. https://doi.org/10.1111/j.1475-2743.1995.tb00493.x

Sela, S., van Es, H. M., Moebius-Clune, B. N., Marjerison, R., Melkonian, J., Moebius-Clune, D., Schindelbeck, R., & Gomes, S. (2016). Adapt-N Outperforms Grower-Selected Nitrogen Rates in Northeast and Midwestern United States Strip Trials. *Agronomy Journal*, *108*(4), 1726–1734. https://doi.org/10.2134/agronj2015.0606

Seybold, E. C., Dwivedi, R., Musselman, K. N., Kincaid, D. W., Schroth, A. W., Classen, A. T., Perdrial, J. N., & Adair, E. C. (2022). Winter runoff events pose an unquantified continental-scale risk of high wintertime nutrient export. *Environmental Research Letters*, *17*(10), 104044. https://doi.org/10.1088/1748-9326/ac8be5

Shennan, C. (1992). Cover crops, nitrogen cycling, and soil properties in semi-irrigated vegetable production systems. *HortScience*, *27*(7), 749–754.

Sideman, B., McKeag, L., Smart, A., & Wallingford, A. (2023). *New England Vegetable Management Guide*. New England Vegetable Guide. https://nevegetable.org/

Smith, M., & Henderson, E. (Eds.). (1998). *The Real Dirt: Farmers Tell about Organic and Low-Input Practices in the Northeast* (2nd edition). Northeast Region SARE / ACE program.

Snapp, S. S., Swinton, S. M., Labarta, R., Mutch, D., Black, J. R., Leep, R., Nyiraneza, J., & O'Neil, K. (2005). Evaluating Cover Crops for Benefits, Costs and Performance within Cropping System Niches. Agronomy Journal, 97(1), 322–332. https://doi.org/10.2134/agronj2005.0322a

Stute, J. K., & Posner, J. L. (1995). Synchrony between Legume Nitrogen Release and Corn Demand in the Upper Midwest. *Agronomy Journal*, *87*(6), 1063–1069. https://doi.org/10.2134/agronj1995.00021962008700060006x

Sullivan, D., Andrews, N. (Nick), & Brewer, L. (2012). *Estimating Plant-Available Nitrogen Release from Cover Crops* [Extension Catalog publication]. Extension Communications; Oregon State University Extension Service. https://Extension.oregonstate.edu/catalog/pub/pnw-636-estimating-plant-available-nitrogen-release-cover-crops

Sullivan, D. M., & Heinrich, A. (2016). Providing organic nutrient management guidance to processed vegetable growers: Oregon Processed Vegetable Commission Continuing Project Report, 2016. Oregon State University Extension Service.

Sullivan, D. M., Peachey, E., Heinrich, A., & Brewer, L. J. (2020). Nutrient and soil health management for sweet corn (western Oregon). Oregon State University Extension Service.

Van Den Bossche, A., De Bolle, S., De Neve, S., & Hofman, G. (2009). Effect of tillage intensity on N mineralization of different crop residues in a temperate climate. *Soil and Tillage Research*, *103*(2), 316–324. https://doi.org/10.1016/j.still.2008.10.019

Voisin, A.-S., Salon, C., Munier-Jolain, N. G., & Ney, B. (2002). Quantitative effects of soil nitrate, growth potential and phenology on symbiotic nitrogen fixation of pea (Pisum sativum L.). *Plant and Soil*, *243*(1), 31–42. https://doi.org/10.1023/A:1019966207970

Wagger, M. G. (1989). Time of Desiccation Effects on Plant Composition and Subsequent Nitrogen Release from Several Winter Annual Cover Crops. *Agronomy Journal*, *81*(2), 236–241. https://doi.org/10.2134/agronj1989.00021962008100020020x

Warman, P. R. (2005). Soil Fertility, Yield and Nutrient Contents of Vegetable Crops after 12 Years of Compost or Fertilizer Amendments. *Biological Agriculture & Horticulture*, *23*(1), 85–96. https://doi.org/10.1080/01448765.2005.9755310

White, A., Faulkner, J., Sims, S., Tucker, P., & Weatherhogg, K. (2018). Report of the 2017-2018 New England Adaptation Survey for Vegetable and Fruit Growers. *Department of Plant and Soil Science*, *University of Vermont*.

Wickham H, François R, Henry L, Müller K (2022). _dplyr: A Grammar of Data Manipulation_. R package version 1.0.10, <https://CRAN.R-project.org/package=dplyr>.

Wienhold, B. J., & Halvorson, A. D. (1999). Nitrogen Mineralization Responses to Cropping, Tillage, and Nitrogen Rate in the Northern Great Plains. *Soil Science*

Society of America Journal, *63*(1), 192–196. https://doi.org/10.2136/sssaj1999.03615995006300010027x

Williams, M. M. (2008). Sweet Corn Growth and Yield Responses to Planting Dates of the North Central United States. *HortScience*, *43*(6), 1775–1779. https://doi.org/10.21273/HORTSCI.43.6.1775

Zotarelli, L., Scholberg, J. M., Dukes, M. D., & Muñoz-Carpena, R. (2008). Fertilizer residence time affects nitrogen uptake efficiency and growth of sweet corn. *Journal of Environmental Quality*, *37*(3), 1271–1278. https://doi.org/10.2134/jeq2007.0460

CHAPTER 3: A PARTICIPATORY RESEARCH APPROACH TO IMPROVE HIGH TUNNEL TOMATO PRODUCTION

3.1 Introduction

"High tunnels" or "hoophouses" are semi-permanent structures that look like greenhouses and are widely used by vegetable growers throughout the Northeast. High tunnels are distinct from greenhouses because they lack a permanent foundation, are usually passively ventilated, are sheathed in plastic, and are primarily used to grow crops in the soil (Rudisill et al., 2015; Wells & Loy, 1993). Although high tunnels vary in shape, size, and degree of automation, most in the Northeast are built to withstand snow and are used to extend the growing season and produce crops year-round. Farmers growing in high tunnels report higher yields, easier disease and pest management, improved economic stability, and an increased quality of life (Fitzgerald and Hutton, 2012; Bruce et al., 2021).

Tunnels protect crops in extreme weather events and play an increasingly important role in helping farmers produce crops in the face of the climate crisis (Foust-Meyer & O'Rourke, 2015). The plastic covering on a tunnel protects the soil and crops from rain, thereby reducing nutrient losses, saturation, and ponding. Crop health and produce quality are improved because the plastic keeps rainfall off plants, reducing disease pressure. Finally, tunnel growers have the ability to keep many pests out of tunnels through the use of exclusion insect netting. This strategy protects crops from pest damage and can eliminate reliance on pesticides (Ingwell & Kaplan, 2019; Wells & Loy, 1993).

Definitions of "high tunnels" are inconsistent and previous efforts to obtain data about tunnels have been variable (Carey et al., 2009). It is well known that tunnel growing is different than field growing, and the intensive nature of tunnel production requires a different approach to management of long term soil fertility (Montri & Biernbaum, 2009; Reeve & Drost, 2012). In recent years, growers have recognized these issues and requested more technical information on managing soil fertility in tunnels (Sideman et al., 2019).

This chapter describes an agroecological approach to the study of on-farm management strategies that impact high tunnel outcomes, specifically with regards to in-ground tomato production. I provide a literature review of high tunnel soil management, growing practices, and soil testing protocols, describing gaps in current information and research. I then describe a participatory project I conducted with farmers in Vermont, Massachusetts, New York, and Maine to understand how improved nutrient recommendations and other production practices affect soil fertility and crop performance in high tunnels. I conclude with ideas for future research and mechanisms to provide support to growers.

3.1.2 Value of high tunnels

Despite farmers' increased reliance on high tunnels for farm viability, data that describes their economic value is lacking. The acreage in high tunnel production is largely unknown, partially because the U.S. Department of Agriculture's National Agricultural Statistics Service (NASS) groups information on all forms of "protected cultivation" together (e.g. high-tech glass greenhouses and low-tech plastic-covered high tunnels). However, the USDA NASS reports that that the number of farms in the U.S. growing crops “under cover” tripled between 1998 and 2019, as did the value of sales of those crops (Bruce et al., 2021; USDA, 2021).

Tomatoes are the most widely grown high tunnel crop in Vermont and the Northeast because they utilize vertical space well, have strong market demand, and tunnel production significantly improves yield and quality, when compared to field grown tomatoes (Carey et al., 2009). Tunnel tomatoes are also more profitable than field tomatoes (Conner et al., 2010; Nian et al., 2022), with reported yields averaging between 9.76 and 14.6 kg/m^2 and net returns three times higher than those that were field grown (Galinato & Miles, 2013). Tomatoes in high tunnels ripen approximately one month ahead of field tomatoes, allowing growers to charge higher prices and face less market competition (Reeve & Drost, 2012). In Vermont, a cost of production study with nine organic farms conducted by the Northeast Organic Farmers Association of Vermont (NOFA-VT) showed an average net profit from tunnel tomatoes that is equal to $370,000 /ha. (NOFA-VT, 2019). In comparison, the 5-year yield average for field tomato harvests in Vermont and New England is about 11 metric tons/ha (NASS, 2017), which at market value of $1.20/kg (NOFA-VT, 2019) equals gross sales of $74,000/ha.

An additional factor motivating growers to grow in high tunnels is the USDA’s Natural Resource Conservation Service (NRCS) Environmental Quality Incentive Program (EQIP), which began the “High Tunnel System Initiative” in 2010. This program offers growers a generous payment based on the square footage of the tunnel. The USDA-NRCS provided funding for 664 high tunnels in Vermont between 2010 and

2021 (VT state resource conservationist, personal communication, 2021). With 709 farms reported to be selling vegetables by the 2017 Census in Vermont, the NRCS high tunnel initiative has played a significant role in high tunnel adoption in Vermont.

3.1.2 High tunnel soil health

Soil health, which is defined by the Natural Resource Conservation Service (NRCS, 2023) "as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans," is a key component of successful high tunnel growing, especially for organic growers (Knewtson, Janke, et al., 2010; Knewtson et al., 2012; Montri & Biernbaum, 2009; Reeve & Drost, 2012). High tunnels create a distinct environment with altered soil health characteristics (Eaton, 2016; Lei & McDonald, 2019; Reeve & Drost, 2012). Managing tunnel soil health can be a challenging adjustment for farmers accustomed to growing in the field because of the intensity of production, high inputs, and lack of rainfall (Knewtson et al., 2010; Montri & Biernbaum, 2009). Growers employ different management strategies in tunnels which may lead to additional challenges over time, including limited crop rotation and lack of cover cropping (Knewtson, Carey, et al., 2010).

Many tunnel growers have relied on a "feed the soil" approach, with high applications of compost, mulches, and other organic amendments but often without soil testing (Knewtson, Carey, et al., 2010; Montri & Biernbaum, 2009; Reeve & Drost, 2012). Over time, these practices lead to soil high organic matter levels and soils that are highly buffered with excellent water and nutrient retention (Grubinger, 2012; Montri & Biernbaum, 2009), but it can also result in having excessive and unbalanced nutrients

(Reeve & Drost, 2012). The warmer and drier tunnel environment alters microbe activity and subsequent nutrient mineralization rates, providing a quicker burst of nutrients than is typical in field production (Lei & McDonald, 2019; Marshall et al., 2016; Montri & Biernbaum, 2009). A challenge particular to organic tunnel growers is to understand and match the altered mineralization rate of organic amendments to crop uptake needs (Reeve & Drost, 2012; Rudisill et al., 2015).

Tunnel tomatoes can utilize a high rate of N fertilizer, which can result in improved yields in greenhouse and tunnel tomatoes (Ward, 1964; Wittwer & Honma, 1979) but excessive available N can lead to overly vegetative plants and reduce yields (Goldy, 2012; L. W. Jett, 2006; Mefferd, 2017). Tunnel tomatoes demonstrate the highest N demand before fruiting, with sustained N needs throughout production (Reid & Machanoff, 2018). Very little literature exists specifying N rates for high tunnel tomatoes, especially with regard to organic materials (Marshall et al., 2016). The form of N most available to plants in a tunnel environment is nitrate (NO_3^--N), which is produced when organic nitrogen is mineralized by soil microorganisms (Brady & Weil, 1996). In the field, nitrate may be quickly leached by rain, but in tunnels it can remain in the soil profile until utilized by a crop. This offers tunnel growers an advantage because available N measured by soil testing can help guide the application of soil amendments.

Potassium (K) is an extremely important nutrient for tomatoes, particularly for ripening and fruit quality (Ramirez et al., 2009; R. G. Sideman et al., 2020). K deficiency can lead to foliar disorders (Pujos & Morard, 1997) and fruit disorders, such as yellow shoulder and internal white tissue (Eaton, 2016; Hartz, 1999). Fruit disorders are impacted by factors such as fruit temperature, plant variety, water, and concentration of other cations. (Hartz, 1999). Although research has shown that fertilizer K can reduce the incidence of these problems, critical soil test K levels for optimum high tunnel tomato fruit yield and quality have not been defined (R. G. Sideman et al., 2020).

3.1.3 High tunnel tomato nutrient needs

In the 1960's and 1970's, experiments with nutrient application rates in heated greenhouses in Michigan demonstrated that by increasing N and K application rates 3-4 times above field recommendations, soil-grown greenhouse tomato yield increased dramatically (Ward, 1964; Wittwer & Honma, 1979). Agriculture Canada (Papadopoulos, 1991) recommends similarly high nutrient application rates for soil grown greenhouse tomatoes; however, it is important to note these studies and recommendations are based on heated tunnels using conventional fertilizers.

In recent years, several efforts in the Northeast have been dedicated to understanding high tunnel yield potential and associated nutrient needs. In 2011, a preliminary study in Vermont documented tomato yield in an established tunnel at over 13 kg of fruit per square meter (Grubinger, 2012), which is equivalent to 147 metric tons per ha. In 2016, Sideman et al. conducted research in Maine and New Hampshire high tunnels looking at critical K levels, specifically examining the relationship between soil test K levels and incidence of yellow shoulder (R. Sideman et al., 2020). Their work concludes that improving tunnel nutrient management is more complex than simply adjusting soil nutrient levels; a comprehensive, cultural practice-based approach is necessary to improve outcomes related to nutrient dynamics (R. G. Sideman et al., 2020).

In 2018, a collaborative effort called the "New England High Tunnel Survey" (NEHTS) was initiated by Extension professionals around New England to conduct a broad analysis of growing practices in tunnels. Twenty farms and Extension personnel from five states participated in the project. A significant outcome of this work was revised nutrient recommendations that are now utilized by the UMaine soil testing lab and regional Extension specialists. The report also provided a list of cultural practice recommendations, noting that "additional research is needed to quantify the impact of different management and fertilization practices" (Campbell-Nelson et al., 2018). This chapter examines outcomes in high tunnels utilizing these revised nutrient recommendations.

3.1.4 Development of high tunnel soil testing protocols

Soil test labs calculate nutrient recommendations in proportion to nutrient deficits relative to the critical soil test level (Hoskins et al., 2016). Soil tests used in high tunnels have historically been based on field production yields (Hoskins et al., 2016; B. Sideman et al., 2019, 2023). Since high tunnel soils behave quite differently than field soils, using field-calibrated soil tests in greenhouse soils often underestimates the nutrient needs of tunnel tomatoes and can lead to deficiencies (Grubinger, 2012; Hoskins et al., 2016; Montri & Biernbaum, 2009; Reeve & Drost, 2012; Rudisill et al., 2015).

In 2011, the University of Maine Analytical Lab and Maine Soil Testing Service (UMaine) began offering high tunnel soil testing packages. UMaine uses the modified Morgan's solution (typically for field soil tests) to measure extractable nutrients, and the saturated media extract (SME, typically for potting soil tests) to measure water-soluble nutrients (Hoskins et al., 2016) (These testing procedures are described in more detail in "2.3.2 Methods"). As plants remove soluble nutrients, they are theoretically replenished from nutrients in reserve, microbial activity, or mineralization (Thongsin, 2011). UMaine's focus on high tunnel soil testing and support from Extension specialists to offer specific tunnel recommendations since 2011 has enabled an estimated thousands of farmers to have a better estimate of nutrient availability in tunnel soils (Grubinger, 2012; Hoskins et al., 2016; Reeve & Drost, 2012).

3.2 Research questions

This project sought to understand the relationship between specific high tunnel production practices and horticultural outcomes such as soil fertility measures and crop yield and quality. This chapter centers around two research questions:

1. In tomato high tunnels, what are the relationships among measures of soil fertility, nutrient applications, cultural practices, and marketable crop yield?

2. What production practices can be easily improved to help growers maximize marketable high tunnel tomato yield?

3.3 Research approach

I approach this study as an Extension professional with the University of Vermont Extension and as a commercial farmer with over two decades of experience growing tomatoes in high tunnels. My positionality and existing relationships with farmers directed and influenced this work. My hope with this work was to develop mechanisms to integrate a scientific approach to high tunnel soil nutrient recommendations that integrate specific farm context (such as soils, location, labor, markets, and financial constraints) (Bruce et al., 2021).

To accomplish these goals, I used a modified Participatory Action Research (PAR) approach to facilitate farmer input and to improve Extension to farmer collaboration (Mapfumo et al., 2013; Méndez et al., 2017). This project relied heavily on farmer self-reporting, which aligns with the PAR principle of equalizing the input of all participants in research projects (López-García et al., 2021). The PAR process was constrained in this study by both the inherent limitations of a two-year grant and the COVID-19 lockdown, which occurred during the first months of this project in March 2020.

There are many pedagogical overlaps between PAR and my Extension work. Like many Extension professionals, I focus on peer to peer learning and implement collaborative models of information transfer (Birkhaeuser et al., 1991; Pan, 2014). The success of PAR in this project is illustrated by the continued engagement and collaboration with the participant farmers.

3.4 Methods

3.4.1 Farmer recruitment

Between December of 2019 and January of 2020, invitations to the project were posted on the Vermont and Maine vegetable and berry growers' listserv (750 and 417 subscribers, respectively), and in the UMass Extension Vegetable notes publication (1330 subscribers). While soliciting farm participation, farmers provided feedback on the project concept, which allowed for further refinement of the research objectives, data collection methods, and desired outcomes. Farmers also discussed what level of participation suited them and what incentives would support their engagement.

Each grower interested in participating completed an on-line intake form detailing their high tunnel tomato production practices, including plant spacing, variety, timing of planting, as well as their goals for tunnel growing. Participants were specifically asked to only grow red hybrid indeterminate tomatoes in the study, so that outcomes could be compared. By March of 2020, the project had 52 registered participants.

Farmers were asked to read and sign a letter of commitment to the project. Each season of participation, farmers were guaranteed up to two free high tunnel soil tests (value $60 USD), customized recommendations, and a $100 credit to Johnny’s Selected Seeds (Winslow, ME) or High Mowing Seeds (Wolcott, VT). When farmers planted their tunnels, they were asked to complete a second on-line form detailing specifics such as tunnel dimensions, plant spacing, varieties, etc. This information formed the basis of data for understanding each farm’s context.

3.4.2 Soil sampling protocols

Growers who joined the project agreed to submit high tunnel soil tests by March 1 of both project years, 2020 and 2021, which was then analyzed by the UMaine soil testing lab. Farmers used random composite sampling methods, taking 10-15 samples in a zig zag pattern throughout the tunnels, measuring 15-20 cm deep in the soil. They then took 0.5 liters of sampled soil, packed it in plastic bags and mailed it to the UMaine laboratory for analysis.

The UMaine soil testing lab uses two different extracts to analyze high tunnel soils. First, the modified Morgan extract is used as a “universal” extractant, meaning all major macronutrients and many micronutrients can all be measured in the one extract. This analysis can be used to predict nutrient availability over the course of a season. UMaine uses methods detailed by Wolf and Beegle (2011) and developed by McIntosh (1969) (McIntosh, 1969; Wolf & Beegle, 2011).

Second, the saturated Media Extract (SME) is a water extract of a soil sample. It measures nutrients that are water soluble and immediately available for plant uptake in the presence of water. UMaine uses methods developed by the University of Michigan (Warnke, 1983) that measures electrical conductivity, pH, soluble salts, and important plant nutrients. Results are reported as ppm (mg/L) (Warnke, 2011).

Farmers received results from the UMaine lab with nutrient and amendment recommendations generated from both analyses printed on the soil test. The recommendations from UMaine are based on the NEHTS, which are based on “yield goals” (low, medium, good, high) (Campbell-Nelson, 2018). The UMaine soil testing lab gives recommendations for a “good” yield based on the NEHTS, which is 14.6 kg m^2.

Each farm then received customized recommendations within two weeks after sample submission to UMaine. An email was sent to the farmer with comprehensive nutrient recommendations including amendments rates, sources, and timing. These recommendations were generated over the course of several months as farms soil tested between December and March. Vermont farmers who sent high tunnel soil tests to UMaine but did not participate in the project also received recommendations. During

2020 and 2021, recommendations were developed for a total of 242 tunnels on a total of 81 farms. Fifty-two tunnels were enrolled for both 2020 and 2021.

3.4.3 Data collection

Participants were responsible for providing yield data from the tunnels enrolled in the project at the end of each season. Many farmers expressed that they were challenged by tracking data, specifically with regards to limited staff and other complications related to the COVID-19 pandemic. In response, project expectations were modified to align with farmer capacity. Rather than asking farmers to weigh and record each harvest, they could weigh a typical harvest tote and record the number of totes harvested, providing a total harvest number at the end of the season. Farmers who did not submit yield data at project end were contacted by phone or email and asked to provide best estimates of yield. Data was scrutinized and confirmed with farmers to ensure accuracy. This method of farmer-reporting enabled collection of data from a large number of farms spread across Vermont, Maine, Massachusetts, and New York. It is important to acknowledge, however, that relying on farmer reports undoubtedly reduces the accuracy of the data.

3.5 Definitions of practices

Square meter per leader or stem is the plant density based on the number of stems or leaders per square meter. The tomatoes in this study were all indeterminate tomatoes, meaning that they continually grow throughout the season. The plants are pruned and trellised vertically (Ivy, 2014). Some growers train the plants to have one main growing point or stem, others have two main growing points, often called “leaders” (Sweeney & Gailans, 2020).

Planting date is the date that tomatoes were transplanted into the high tunnels. Most plants were started from seed ~8 weeks prior and grown in a heated greenhouse. Transplants are typically in 12 cm square pots with ~2100 cubic cm of potting soil.

Type of heat refers to supplemental heat for early planting dates and to increase the rate of plant growth. We asked farmers if they use “air” or “ground” heat on the intake form; “air” implies propane, oil, cord wood, or wood pellets that are burned to warm the tunnel atmosphere. Most of these systems are outfitted with blowers and circulating fans and are controlled by a thermostat. “Ground heat” refers to radiant systems, with circulating tubes of water buried beneath the root zone of the plants. These systems are usually powered by an electric or propane hot water heater. Temperature inside the tunnels was not monitored in this study.

Number of drip lines refers to the number of polyethylene tubing with regularly spaced emitters placed on the soil at the base of crops. Drip tape, usually 8 to 10 millimeters thick, runs along the surface of the soil. Dripper or emitter spacing is typically 12 to 36 cm (L. W. Jett, 2006). For the purposes of this project, farmers were asked to report how many drip lines were on each row of tomatoes.

Grafted tomatoes are the combination of a rootstock with desirable qualities (disease resistance and vigor), with a scion (or top portion of a plant) with desirable fruit quality, yield, and flavor. Grafting is an increasingly common practice for tunnel growers (Nian et al., 2022). Growers in the study were asked to report whether or not they planted grafted red indeterminates in the study area but did not report on rootstock variety.

Tomato variety is the cultivar of red hybrid indeterminate tomato growing in the study area. Red hybrid indeterminates are the common type of tomato grown in the region. Most are disease resistant and highly productive (Johnny's Selected Seeds, Winslow, ME).

Ground cover is the mulch used for the soil between plant rows, selecting from a list that included: woven black landscape fabric (usually 3.2 oz), black plastic mulch, white plastic mulch (usually 1.5 mm), straw, or bare soil.

Fertilizer applied is the amendment type, rate, method of application, and date(s) applied to the study area. Farmers were requested to match amendments applied with recommendations I provided as part of the project. For data analysis, these amendment rates were converted to rates of applied N, P, and K expressed in Kg/ ha^{-1}.

3.6 Data analysis

Data analysis was conducted using the statistical programming language "R" (R Core Team 2022) to examine the significance of each factor on reported yields. One way ANOVA models were used to test marketable yield against the following factors: soil test data, nutrient inputs, and practices, including number of irrigation lines, grafting, ground cover, tomato variety, and type of heat.

3.7 Results

Data was collected from 46 tunnels on 26 unique farms over the course of the 2020 and 2021 growing seasons. The farms are in Maine, Massachusetts, New Hampshire, New York, and Vermont, ranging from USDA plant hardiness zones 3-5.

Farms represent a mix of organic and conventional and of varying scales. Tunnels varied in size, shape, style, ventilation, automation.

3.7.1 Farmer goals

Farmers expressed a strong interest in improving overall tunnel soil health, more accurate nutrient management, better yields and improved fruit quality. Farmer responses to the project intake form are summarized in Table 7.

Table 7: Participant farmer responses to intake question "What are your soil fertility goals for the tomato tunnels"

Farmer objective	Number of responses
Healthy soil	11
Nutrient management	13
Fruit quality	8
Yields	11

3.7.2 Nutrients

Prior to this project, 21% (n=10) of the tunnels were not soil tested annually, with no prior guidance on soil fertility. Soil tests taken at the start of the project in early spring of 2020 showed that 92% of tunnels (n=42) were low in N and 90% (n=41) tunnels were low in K according the NEHTS recommendations. An average of 1.3 kg N and 3.9 kg K /100 m^2 was applied by all farms in the study to meet the recommendations.

One-way ANOVA was used to analyze the relationship between pre-plant nutrient levels and yield, specifically examining soil organic matter, pH, nitrate, phosphorus, and potassium. There are no significant differences between any preplant soil test nutrients levels and yield. The impact of applied nutrients on marketable yield was also examined using ANOVA, revealing no significant differences.

3.7.3 Practices

Table 8: Effects of farm practices on marketable yield (kg/ sq meter)

Factor	F-statistic	P-Value
Square meter per leader or stem	5.211	0.0273 *
Type of heat	0.791	0.46
Number of drip lines	2.825	0.1
Grafted tomatoes	0.012	0.913
Planting date	1.286	0.275
Tomato variety	0.366	0.868
Type of ground cover	0.484	0.786
Fertilizer applied (N)	0.005	0.943
Fertilizer applied (K)	0.437	0.512

Table 8 summarizes the effects of farm practices on marketable yield. Using one-way ANOVA tests, the only factor that had a significant effect on marketable yield was planting density. However, several trends emerged in some practices. By using the 'Dyplr" (Wickham et al., 2022) function in R to filter within practices significant findings in specific practices are reported below and summarized in Figure 7 and Table 9.

Square meter per leader or stem. Growers reported a wide range of planting density, from 0.28 to 0.93 meters^2 per leader/ stem. There is a significant effect on yield (p=0.0273) when leader spacing is between 0.35-0.4 m^2. As seen in Figure 7, there are many outliers in reported yield but overall, low yields per square meter were associated with more space per stem.

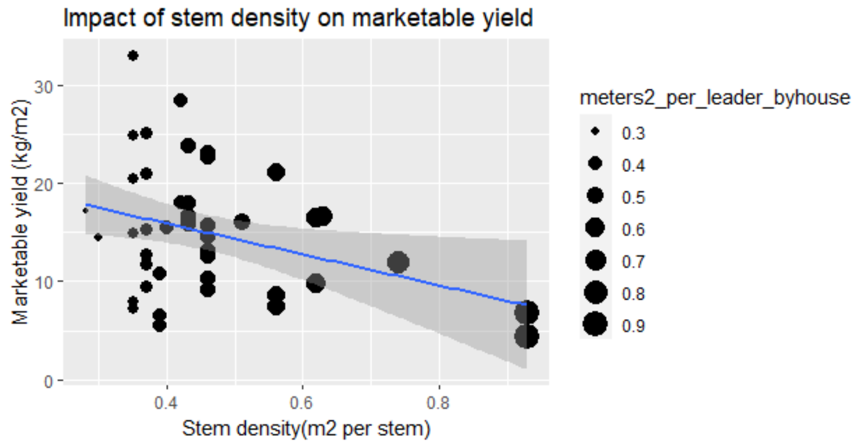

Figure 7: Relationship between planting density measured by number stems or leaders per square meter and marketable yield. Low yielding outliers were due to disease and market factors.

Planting date. There was a range of planting dates from March 3-June 3, but the majority of tunnels (n=24) were planted between April 12 and May 17 in both 2020 and 2021. The highest yields were from tomatoes planted the week of April 12-19 with a mean yield of 20.9 kg/m^2. For both years, there is a significant difference (p=0.001) using t-tests to compare mid-April planting dates (April 12-19) with the end of April (April 20-May 3), which has a mean yield of 13.35 kg/m^2.

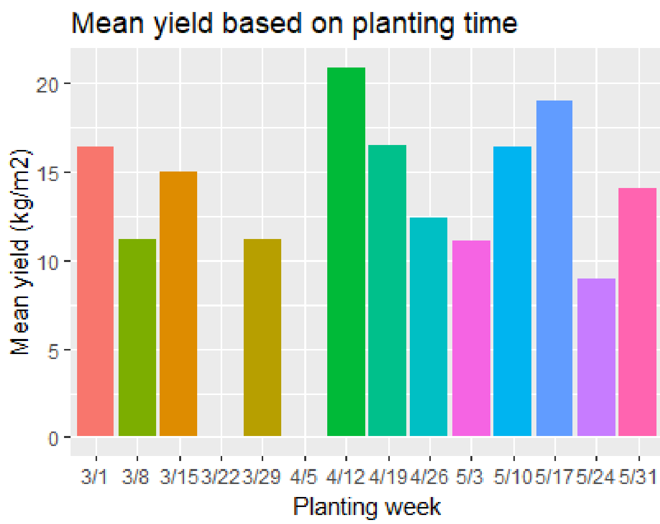

Figure 8: Mean yield for both study years based on planting time. Reported yield was highest between 4/12 and 4/19 in both 2020 and 2021.

Type of heat. The majority of tunnels in the study were unheated (n=35), with the remainder either heated with furnace air heat (n=6) or with radiant soil heat (n=5). There is no significant difference between the types of heat but there is a trend towards higher yield with air heat and lower marketable yield reported from the ground heat than with no heat at all.

Number of drip lines. The majority of tunnels (n=23) have 2 drip lines per row of plants. No data was collected in this study reflecting soil moisture levels or frequency, duration, and volume of water delivered to plants over the season. This data revealed a trend of higher yield using t-tests to compare 1 to 3 drip lines (p=0.0276) and 1 to 2 lines (p=0.0353).

Table 9: Mean marketable yield based on number of drip lines per row of tomatoes using Fisher's LSD.

Number of drip lines	Mean marketable yield (kg/m2)
3	17.11429 a
4	16.16923 a
2	14.67619 ab
1	8.95 b

Grafted tomatoes. 24 farms grafted tomato plants and 22 did not. There was no significant difference found in yield, with mean yield almost exactly the same values between the two treatments.

Tomato varieties. Cultivars grown for this study were (percent of total varieties in study in parentheses): Geronimo (31%), Big Dena (29%), Rebelski (21%), Big beef (9%), (Johnny's Selected Seeds, Winslow, ME). Varieties that were less than 5% of the total planted were: Estiva (Johnny's Selected Seeds, Winslow, ME), Arbason, Caimen, Fredrick, and Lola (High Mowing Seeds, Wolcott, VT). The average yield is similar among varieties, with no significant differences found between variety and yield.

Type of ground cover. Farmers reported ground cover used: woven black landscape fabric (n=18), black plastic (n=14), bare soil (n=9), white plastic (n=4), straw mulch (n=2), and cover crops (n=1). There were no significant differences between the types of mulches used and no direct relationship between type of ground cover and marketable yield (Figure 9).

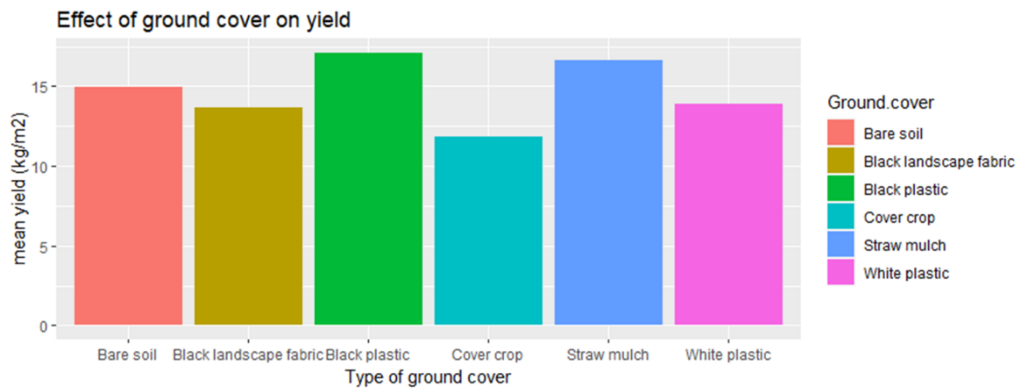

Figure 9. Ground cover treatment impacts on marketable yield of tomatoes (kg/m2).

Fertilizer applied – One-way ANOVA was used to test the significance of applied fertilizer (kg N, P, and K) to meet the NEHTS recommendations. There was no significant relationship found between amount of fertilizer applied and marketable yield.

3.8 Discussion

The first goal of this study was to demonstrate yield improvements from the NEHTS nutrient recommendations. The average yield number achieved in this study,15.24 kg/m^2, slightly exceeds the “good” goal in the NEHTS of 14.6 kg m^2 and is also significantly higher than many previously published yield targets of ~10 kg/ m^2 (Hodge et al., 2019; L. Jett, 2004).

This lack of significant correlation between marketable yield, preplant nutrient levels, and applied fertilizer rates demonstrates the successful results of implementing the NEHTS recommendations. In other words, regardless of soil test deficiencies, when tunnels are amended in accordance with the NEHTS guidelines, high tunnel soil fertility improves, and good yields can be achieved in a single season. Feedback from farmers also affirm this success, with100% of the farms that responded to a post study survey (n=18) noting yield and quality improvements within a single season compared to previous years (unfortunately, no prior seasons' records were shared for quantitative comparison).

The second goal of this study was to understand the impact farm practices have on yield. It is important to note that many variables affecting outcomes are beyond a grower's control (weather, markets, labor, etc.). The aim of this project was to identify and analyze the effectiveness of practices a grower can easily implement or adjust.

Stem density. Statistical data analysis demonstrated that stem/ leader density has significant influence on marketable yield. Earlier work on greenhouse tomato spacing by Wittwer and Honma suggested that "there is no agreement among growers as to the most desirable distance …between plants" (p. 45), but the authors say that the optimum spacing they have found was 0.32-0.42 m^2 per plant (Wittwer & Honma, 1979). The NEHTS recommends a similar stem density between 0.27 and 0.46 stems/ m^2. This study further emphasizes the importance of densely spaced stems in high tunnel tomatoes; in this study, yield is highest at 1 stem or leader per 0.35-0.4 m^2.

Since tunnels are economically valuable spaces, maximizing output is important to growers. However, there may be yield limitations at very high stem density due to diseases and physical crowding (Maynard, 2019), yet these limitations were not found at the densities examined here. Factors that no data was collected on, such as tunnel size, ventilation, and pruning practices likely influence the limitations of increased stem density. This is illustrated in Figure 8 by data points from tunnels with low marketable yield but with tightly spaced stems. Several of these tunnels are poorly ventilated and suffered yield losses to disease. This suggests further examination of the importance of ventilation and disease management in densely planted tunnels. Two other farms with high stem density but low yield data removed plants before the majority of fruit ripened because they did not have a market for them. These results reveal that even when practices are optimal, other factors may impede success.

Planting date. By analyzing the impact specific week numbers have on yield, this study identifies an optimal planting window for tunnels in the region. Growers establishing plants during a critical planting window between April 12 and April 19 had much higher yields than those planted before or after). It is important to note, however, that most growers need reliable yields for as much of the season as is feasible. Further research to understand the net profitability associated with earlier and later planting could help clarify this uncertainty.

Other studies have shown that an early planting date can allow growers to capture high prices and secure local markets (Conner et al., 2010; Hunter et al., 2012; Reeve & Drost, 2012). Tunnels without supplemental heat in the Northeast are usually planted in mid-April and ripen between 4 to 5 weeks before field tomatoes (Knewtson, Carey, et al., 2010; Reeve & Drost, 2012). Some studies have also shown that planting date had no effect on overall yield (Rogers & Wszelaki, 2012), but other studies show that later planting dates sacrifice early season yield (Hunter et al., 2012). In unheated tunnels, tomatoes planted in cool early season soil temperatures may also suffer from nutrient deficiencies (Gent, 1992).

Heat. In this study, over half of the tunnels (9/16) planted before April 12 had heat, whereas no tunnels planted after April 12 had air heat. Air heat provided insurance against total crop loss due to freezing temperatures (Both et al., 2007) and supported slight increases in overall yield. Previous research has shown that the early season economic gain associated with early planting dates is significantly improved with the use of heat in tunnel production, but the same study reports no significant effect on total marketable yield (Hunter et al., 2012). A detailed cost-benefit analysis would help growers understand precisely under what conditions an investment in heat would pay off.

Irrigation. The recommendations in the NEHTS note that adequate moisture is necessary for tunnel production and recommended that farmers on lighter soils increase to 4 drip lines per plant row (Campbell-Nelson et al., 2018). This project affirmed these recommendations, demonstrating improved yield when growers use more than 1 line of drip per row of tomatoes. This finding is more complex than merely revealing that plant performance is directly related to an increase in moisture. Granular fertilizers, such as potassium sulfate, require water to be dissolved for plant uptake. Microbes critical to nutrient mineralization also require water to be activated (Drenovsky et al., 2004; Montri & Biernbaum, 2009). Water can create a pulse of microbial activity, resulting in enhanced nutrient mineralization (Schimel, 2018). Increasing the number of drip lines in plant rows increases the volume of soil that is moistened, bringing more nutrients into soil solution available for plant uptake. In other words, even when growers apply adequate nutrients, if there is no water to assist in their delivery to plants, then the nutrients remain dry and unavailable to plants. Improved water delivery can also lead to better fruit quality and reduced cracking (Rogers & Wszelaki, 2012). A future study could more closely examine the relationship between high tunnel watering practices, amendment applications, nutrient availability, and yield.

Grafting. It has been well-reported that grafted plants produce quality fruit for a long duration of the season (Nian et al., 2022; Rivard et al., 2010) but in this study, there was no significant difference between grafted versus ungrafted crop yields. In fact, the average yield was almost exactly the same (~15 kg/m2) regardless of grafting. More research could help reveal the importance of factors like benefits of disease resistance, improved quality, harvest window, etc. to more closely examine the costs and benefits of grafting. This could help farmers decide under which circumstance they should invest in this process.

3.9 Conclusion

This study provides several practical insights into high tunnel tomato growing and offers many suggestions for future research needs. First, the results from two years of research suggest that implementing the NEHTS recommendations leads to improved yields regardless of pre-amendment soil nutrient status. This finding substantiates the expectations of the NEHTS and provides confidence to utilize the recommendations in the future. In other words, this project suggests that growers who implement the NEHTS recommendations are likely to have excellent yield outcomes.

Second, the study highlighted the value of tunnel space. Planting at an optimal density will help farmers improve marketable yield. While we identified an optimal density, it is important to account for the different limitations each farm has to realistically adopt this density. Size of tunnel, airflow, relative humidity, and pruning practices all influence the success of tighter plant spacing.

Third, this project demonstrated that for the regions covered in this study (Vermont, Western Massachusetts, Eastern New York, and Maine), marketable yield was correlated with a planting date during the third week of April, when soils are warm and the day length is increasing. Since this finding is based on two years of data, continued research should be conducted.

Fourth, the relationship among irrigation, soil nutrients, and plant performance is revealed as important in this study, but more research should be done to examine the influences of soil type, crop stage, and weather on yield outcomes. However, a simple conclusion to be drawn here is that in addition to providing plants with an adequate supply of water, more drip lines also enable access to greater soil volume with more microbe activity and nutrients.

Finally, several trends were revealed about the impact practices have on yield, although more research needs to be done to specifically address outcomes related to heating, grafting, ground cover, and variety selection. Many of these practices consume energy, time, and money; helping farmers weigh the costs and benefits as they relate to specific farm scenarios will help tunnel growers sustain their operations in a profitable and efficient manner. In summary, this study suggests that further work should be done to develop a comprehensive, tailored approach to high tunnel recommendations that integrates soil health with farm practices and yield goals.

It is also important to couch this project within an agroecological lens. The rise of high tunnel production may be viewed as a movement driven by farmers seeking a profitable way to grow high quality food, despite global market pressures and threats posed by climate change. The social context is important to understand the limitations farmers face in implementing new practices and recommendations like those made here. High tunnels are a relatively new technology that requires a different set of management skills and knowledge. For some growers, integrating focused tunnel management into existing production systems can be challenging (Bruce et al., 2021; Conner et al., 2010; Janke et al., 2017). Previous work has examined some of the challenges of adopting specific practices for high tunnels (Bruce et al., 2021; Knewtson et al., 2012; Rudisill et al., 2015). Understanding and integrating social factors that relate to the adoption of soil health practices is a concept that is more broadly explored in Chapter 4 of this dissertation. Employing a comprehensive approach to high tunnel management is an exciting next step.

3.10 References

Birkhaeuser, D., Evenson, R. E., & Feder, G. (1991). The Economic Impact of Agricultural Extension: A Review. In *Source: Economic Development and Cultural Change* (Vol. 39, Issue 3).

Both, A. J., Reiss, E., Sudal, J. F., Holmstrom, K. E., Wyenandt, C. A., Kline, W. L., & Garrison, S. A. (2007). Evaluation of a Manual Energy Curtain for Tomato Production in High Tunnels. *HortTechnology*, *17*(4), 467–472. https://doi.org/10.21273/HORTTECH.17.4.467

Bruce, A. B., Maynard, E. T., Valliant, J. C. D., & Farmer, J. R. (2021). Farm Type and High Tunnel Management: Connections between Farm Characteristics and High Tunnel Outcomes in Indiana. *HortTechnology*, *31*(5), 566–576. https://doi.org/10.21273/HORTTECH04783-21

Campbell-Nelson, K. Grubinger, V.,Hoskins, Bruce, Radin Andy ,Sideman, Becky, "2018 New England High Tunnel Survey." ag.mass.edu, 2019. Retrieved from https://ag.umass.edu/sites/ag.umass.edu/files/reports/2018_high_tunnel_survey_report.pdf on 10/24/2023.

Carey, E. E., Jett, L., Lamont, W. J., Nennich, T. T., Orzolek, M. D., & Williams, K. A. (2009). Horticultural Crop Production in High Tunnels in the United States: A Snapshot. *HortTechnology*, *19*(1), 37–43. https://doi.org/10.21273/HORTSCI.19.1.37

Conner, D. S., Waldman, K. B., Montri, A. D., Hamm, M. W., & Biernbaum, J. A. (2010). Hoophouse Contributions to Economic Viability: Nine Michigan Case Studies. *HortTechnology*, *20*(5), 877–884. https://doi.org/10.21273/HORTTECH.20.5.877

Drenovsky, R. E., Vo, D., Graham, K. J., & Scow, K. M. (2004). Soil Water Content and Organic Carbon Availability Are Major Determinants of Soil Microbial Community Composition. *Microbial Ecology*, *48*(3), 424–430. https://doi.org/10.1007/s00248-003-1063-2

Eaton, Connor, Year-round management of high tunnel production systems: spinach and tomato (2016). Master's Theses and Capstones. 1088. https://scholars.unh.edu/thesis/1088

Foust-Meyer, N., & O'Rourke, M. (2015). High Tunnels for Local Food Systems: Subsidies, Equity, and Profitability. *Journal of Agriculture, Food Systems, and Community Development*, 1–12. https://doi.org/10.5304/jafscd.2015.052.015

Galinato, S. P., & Miles, C. A. (2013). Economic Profitability of Growing Lettuce and Tomato in Western Washington under High Tunnel and Open-field Production Systems. *HortTechnology*, *23*(4), 453–461. https://doi.org/10.21273/HORTTECH.23.4.453

Gent, M. P. N. (1992). Yield response to planting date, ventilation and soil temperature on growth and nutrition of tomato high tunnels. *Plant Soil*, *145*, 81–91.

Goldy, R. (2012). *Experience with growing tomatoes in high tunnels: Fertilization, quality and yield*. MSU Extension. Retrieved November 1, 2023 from https://www.canr.msu.edu/news/experience_with_growing_tomatoes_in_high_tunnels_fertilization_quality_and_yield.

Grubinger, V. (2012). *Organic Greenhouse Tomato Nutrition*. University of Vermont Extension. Retrieved October 4, 2023 from http://www.uvm.edu/vtvegandberry/factsheets.

Hartz, T.K. & Miyao, G. & Mullen, R.J. & Cahn, Michael & Valencia, Jair & Brittan, K.L.. (1999). Potassium Requirements for Maximum Yield and Fruit Quality of Processing Tomato. Journal of the American Society for Horticultural Science. American Society for Horticultural Science. 124. 10.21273/JASHS.124.2.199.

Hodge, T., Healy, K., Emerson, B., & Dawson, J. (2019). *Comparing Tomato varieties under organic high tunnel and open field management in the North Central region.* eOrganic.

Hoskins, B., Sideman, R., & Hutton, M. (2016, April 12). Preliminary Soil Test Calibration for High Tunnel Production—Maine Food and Agriculture Center—University of Maine. *Maine Food and Agriculture Center*. https://umaine.edu/mainefoodandagcenter/2016/04/12/966/

Hunter, B., Drost, D., Black, B., & Ward, R. (2012). Improving Growth and Productivity of Early-season High-tunnel Tomatoes with Targeted Temperature Additions. *HortScience*, *47*(6), 733–740. https://doi.org/10.21273/HORTSCI.47.6.733

Ingwell, L. L., & Kaplan, I. (2019). Insect Exclusion Screens Reduce Cucumber Beetle Infestations in High Tunnels, Increasing Cucurbit Yield. *Journal of Economic Entomology*, *112*(4), 1765–1773. https://doi.org/10.1093/jee/toz060

Ivy, A. (2014). *BMPs Proper pruning and training.pdf*. http://www.hort.cornell.edu/expo/proceedings/2015/high-tunnels/BMPs%20Proper%20pruning%20and%20training.pdf

Janke, R. R., Altamimi, M. E., & Khan, M. (2017). The Use of High Tunnels to Produce Fruit and Vegetable Crops in North America. *Agricultural Sciences*, *8*(7), Article 7. https://doi.org/10.4236/as.2017.87052

Jett, L. (2004). *High Tunnel Tomato production*. University of Missouri Extension.

Jett, L. W. (2006). Watering and Fertilizing Tomatoes in a High Tunnel. University of Missouri Extension.

Knewtson, S. J. B., Carey, E. E., & Kirkham, M. B. (2010). Management Practices of Growers Using High Tunnels in the Central Great Plains of the United States. *HortTechnology*, *20*(3), 639–645. https://doi.org/10.21273/HORTTECH.20.3.639

Knewtson, S. J. B., Janke, R., Kirkham, M. B., Williams, K. A., & Carey, E. E. (2010). Trends in Soil Quality Under High Tunnels. *HortScience*, *45*(10), 1534–1538. https://doi.org/10.21273/HORTSCI.45.10.1534

Knewtson, S. J. B., Kirkham, M. B., Janke, R. R., Murray, L. W., & Carey, E. E. (2012). Soil Quality After Eight Years Under High Tunnels. *HortScience*, *47*(11), 1630–1633. https://doi.org/10.21273/HORTSCI.47.11.1630

Lei, L., & McDonald, L. M. (2019). Soil Moisture and Temperature Effects on Nitrogen Mineralization in a High Tunnel Farming System. *Communications in Soil Science and Plant Analysis*, *50*(17), 2140–2150. https://doi.org/10.1080/00103624.2019.1654503

Mapfumo, P., Adjei-Nsiah, S., Mtambanengwe, F., Chikowo, R., & Giller, K. E. (2013). Participatory action research (PAR) as an entry point for supporting climate change adaptation by smallholder farmers in Africa. *Environmental Development*, *5*, 6–22. https://doi.org/10.1016/j.envdev.2012.11.001

Marshall, K., Erich, S., Hutton, M., Hutchinson, M., & Mallory, E. (2016). Nitrogen Availability from Compost in High Tunnel Tomato Production. *Compost Science & Utilization*, *24*(3), 147–158. https://doi.org/10.1080/1065657X.2015.1102663

Maynard, E. (2019). Managing the Environment in High Tunnels for Cool Season Vegetable Production. Retrieved November 1, 2023 from https://www.extension.purdue.edu/extmedia/ho/ho-297-w.pdf

McIntosh, J. L. (1969). Bray and Morgan Soil Extractants Modified for Testing Acid Soils from Different Parent Materials1. *Agronomy Journal*, *61*(2), 259–265. https://doi.org/10.2134/agronj1969.00021962006100020025x

Mefferd, A. (2017). *The Greenhouse and Hoophouse Grower's Handbook—Chelsea Green Publishing*. https://www.chelseagreen.com/product/the-greenhouse-and-hoophouse-growers-handbook/

Méndez, V. E., Caswell, M., Gliessman, S. R., & Cohen, R. (2017). Integrating Agroecology and Participatory Action Research (PAR): Lessons from Central America. *Sustainability*, *9*(5), Article 5. https://doi.org/10.3390/su9050705

Montri, A., & Biernbaum, J. A. (2009). Management of the Soil Environment in High Tunnels. *HortTechnology Hortte*, *19*(1), 34–36. https://doi.org/10.21273/HORTSCI.19.1.34

NASS Vermont full report. (2017). https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_State_Level/Vermont/

Nian, Y., Zhao, R., Tian, S., Zhao, X., & Gao, Z. (2022). Economic Analysis of Grafted Organic Tomato Production in High Tunnels. *HortTechnology*, *32*(5), 459–470. https://doi.org/10.21273/HORTTECH05101-22

NOFA-VT. (2019). *Cost of Production Factsheet*. Retrieved Octbober 4, 2023 from https://www.nofavt.org/resource-library/vegetable-cost-production

NRCS. (2023). *Soil Health | Natural Resources Conservation Service*. Retrieved October 2, 2023 from https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soils/soil-health

Pan, D. (2014). The impact of agricultural Extension on farmer nutrient management behavior in chinese rice production: A household-level analysis. *Sustainability (Switzerland)*, *6*(10), 6644–6665. https://doi.org/10.3390/su6106644

Papadopoulos, A. (1991). Growing greenhouse tomatoes in soil and in soilless media. University of Wisconsin - Madison.

Perkus, E. A., Grossman, J. M., Pfeiffer, A., Rogers, M. A., & Rosen, C. J. (2022). Exploring Overwintered Cover Crops as a Soil Management Tool in Upper-midwest High Tunnels. *HortScience*, *57*(2), 171-180. Retrieved Dec 1, 2023, from https://doi.org/10.21273/HORTSCI15987-21

Pujos, A., & Morard, P. (1997). Effects of potassium deficiency on tomato growth and mineral nutrition at the early production stage. *Plant and Soil*, *189*(2), 189–196. https://doi.org/10.1023/A:1004263304657

Ramirez, L. F., E., J., & G., P. (2009). Potassium affects the lycopene and p-carotene concentration in greenhouse tomato. *Acta Horticulturae*, *821*, 223–228. https://doi.org/10.17660/ActaHortic.2009.821.25

Reeve, J., & Drost, D. (2012). Yields and Soil Quality under Transitional Organic High Tunnel Tomatoes. *HortScience*, *47*(1), 38–44. https://doi.org/10.21273/HORTSCI.47.1.38

Reid, J., & Machanoff, C. (2018). Best Management Practices for Long Term Soil Health and Fertility. Cornell University. Retrieved September 1, 2023 from https://cvp.cce.cornell.edu/soil_health.php.

Rivard, C. L., Sydorovych, O., O'Connell, S., Peet, M. M., & Louws, F. J. (2010). An Economic Analysis of Two Grafted Tomato Transplant Production Systems in the United States. *HortTechnology*, *20*(4), 794–803. https://doi.org/10.21273/HORTTECH.20.4.794

Rogers, M. A., & Wszelaki, A. L. (2012). Influence of High Tunnel Production and Planting Date on Yield, Growth, and Early Blight Development on Organically Grown Heirloom and Hybrid Tomato. *HortTechnology*, *22*(4), 452–462. https://doi.org/10.21273/HORTTECH.22.4.452

Rudisill, M. A., Bordelon, B. P., Turco, R. F., & Hoagland, L. A. (2015). Sustaining Soil Quality in Intensively Managed High Tunnel Vegetable Production Systems: A Role for Green Manures and Chicken Litter. *HortScience Horts*, *50*(3), 461–468. https://doi.org/10.21273/HORTSCI.50.3.461

Schattman, R., Jean, H., Faulkner, J., Maden, R., Grubinger, V., McKeag, L., Nelson, K., Erich, M., Burnett, S., & Ohno, T. (2023). Effects of irrigation scheduling approaches on soil moisture and vegetable production in the Northeastern U.S.A. *Agricultural Water Management*, *287*, 108427. https://doi.org/10.1016/j.agwat.2023.108428

Schimel, J. P. (2018). Life in Dry Soils: Effects of Drought on Soil Microbial Communities and Processes. *Annual Review of Ecology, Evolution, and Systematics*, *49*(1), 409–432. https://doi.org/10.1146/annurev-ecolsys-110617-062614

Sideman, B., Bryant, H., Skinner, M., Sullivan, C. F., Hutton, M., Hoskins, B., & Sideman, E. (2019). *Survey of High Tunnel Practices in Northern New England, 2016 & 2019*.

Sideman, B., McKeag, L., Smart, A., & Wallingford, A. (2023). *New England Vegetable Management Guide*. New England Vegetable Guide. https://nevegetable.org/

Sideman, R. G., Hoskins, B., Hutton, M., Bryant, H., & Sideman, E. (2020). Optimizing potassium application in organically-grown high tunnel tomato (*Solanum lycopersicum*) in the northeastern United States. *Acta Horticulturae*, *1296*, 1085–1092. https://doi.org/10.17660/ActaHortic.2020.1296.137

Sweeney, M., & Gailans, S. (2020). *20.H.High-tunnel-tomato-pruning_FINAL.pdf*. https://practicalfarmers.b-cdn.net/wp-content/uploads/2021/04/20.H.High-tunnel-tomato-pruning_FINAL.pdf

Thongsin, W. (2010). *High Tunnels*. Maine Organic Farmers and Gardeners. Retrieved August 4, 2022, from https://www.mofga.org/resources/season-Extension/high-tunnels/

USDA, N. (2021). *USDA - National Agricultural Statistics Service—Census of Horticulture*. Retrieved from https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Census_of_Horticultural_Specialties/index.php. On 10/24/2023.

Ward, G. M. (1964). Greenhouse Tomato Nutrition—A Growth Analysis Study. Plant and Soil, August 1964, Vol. 21, No. 1 (August 1964), pp. 125-133 Published by: Springer Stable URL: https://www.jstor.org/stable/42932061.

Warnke, D. (1983). Greenhouse Growth Media: Testing and Nutrition Guidelines Michigan State University Extension Service MSU Ag Department of Horticulture

Warnke, D. (2011). Recommended Test Procedures for Greenhouse Growth Media. The Northeast Coordinating Committee for Soil Testing. Retrieved October 25, 2023 from https://www.udel.edu/academics/colleges/canr/cooperative-extension/fact-sheets/soil-testing-procedures-northeastern-US/

Wells, O. S., & Loy, J. B. (1993). Rowcovers and High Tunnels Enhance Crop Production in the Northeastern United States. *HortTechnology*, *3*(1), 92–95. https://doi.org/10.21273/HORTTECH.3.1.92

Wittwer, S. H., & Honma, S. (1979). *Greenhouse Tomatoes, Lettuce and Cucumbers*. Michigan State University Press.

Wolf, A., & Beegle, D. (2011). Recommended Soil Tests for Macro and Micronutrients. Northeastern Regional Publication No. 493. University of Deleware.

CHAPTER 4: UTILIZING MENTAL MODELS TO UNDERSTAND IMPLEMENTAITON OF SOIL HEALTH PRACTICES ON VERMONT VEGETABLE FARMS

4.1 Introduction

The record-breaking rains in Vermont during the 2023 growing season offered a sobering glimpse of what a climate altered future may look like for farmers in Vermont (Galford et al., 2021; Mason et al., 2021). More than ever before, farmers are acutely aware of the critical role soil health practices play in the ability of their land and livelihoods to sustain production in the face of new extremes. Vermont is one of five states identified in the United States as extremely vulnerable to erosion resulting from climate change (Segura et al., 2014). Vegetable farms that grow crops requiring tillage are even more susceptible to soil loss, nutrient leaching, and surface crusting (Stott & Moebius-Clune, 2017). If farmer livelihoods are to survive, especially those of diversified vegetable farms, farmers will need support adapting and implementing soil health practices that withstand erratic weather.

4.1.1 Soil health in Vermont

Soil health, which is defined by the United States Department of Agriculture Natural Resource Conservation Service (NRCS, 2023) as “the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans,” is an increasingly popular concept that lies at a precarious juncture of agriculture and environmentalism. Soil health is frequently used to represent responsible stewardship of the environment by farmers. Large amounts of federal, state, and private funding are devoted to research and incentives that promote soil health improvements as a critical strategy to address the multiple ecological crises of our times (Carlisle, 2016; Dungait et al., 2012).

Soil health in agriculture is likewise a popular topic among vegetable and small fruit growers, particularly in Vermont where farmers are supported by technical assistance from the University of Vermont Extension (UVM Extension), NRCS, and many others. There are many financial incentives available from the USDA NRCS and other programs that are designed to motivate growers to adopt practices such as reduced tillage, nutrient management planning, and cover cropping (Biardeau et al., 2016). Farmers in Vermont also face relatively new state regulations aimed at reducing agricultural runoff and improving water quality (Vermont Agency of Agriculture Food and Markets, 2016). These regulations compel farmers of all types and scales to adopt improved soil health practices like those previously listed. These practices can benefit farms by increasing soil organic matter, water infiltration, microbial activity, nutrient cycling, and reducing fertilizer costs (Magdoff & Van Es, 1993; Norris & Congreves, 2018). Implementation of these practices also provides public benefits, or "ecosystem services", including carbon sequestration, clean water, and reduced greenhouse gas emissions (Hammond Wagner et al., 2019; White et al., 2022).

In the past decade, there has been an increasing focus on the critical role soil plays in sustaining life on the planet, largely due to a heightened awareness of environmental crises including climate change and pressures to increase agricultural production (Karlen et al., 2017). Research has revealed the complexity of soil ecology, with microscopic organisms now recognized for the diversity of functions they provide and their critical role in the production of food (Doran & Zeiss, 2000; Lehmann et al., 2020). Soil organisms are sensitive to farm management and exhibit reduced functionality when disturbed by certain soil health practices, which can lead to degradation of land and agricultural production (Doran & Zeiss, 2000). In order to better understand the connections between farm management and soil health, numerous frameworks have been developed to evaluate soil health (Karlen et al., 2017; Moebius-Clune et al., 2016; Neher et al., 2022).

However, the inherent diversity and complexity of soil ecology makes it challenging to develop consistently measurable soil health outcomes that can quantify impacts of practices on soil health (Bagnall et al., 2020; Karlen et al., 2017; Wade et al., 2022). Perhaps more importantly, there often exists a gap in desired soil health outcomes between different stakeholders; researchers usually focus on soil health metrics, whereas farmers are interested in improving soil health for crop productivity (Wade et al., 2022). Service providers, policy makers, and others often seek to bridge this gap by motivating farmers to implement new soil health practices aimed at satisfying both outcomes. For example, cover cropping is widely promoted, often with financial incentives, as a practice that has multiple environmental and crop production benefits. However, researchers have found that farmer behavior change is not always linked to known benefits, as is the case with cover cropping, and as a result, practice implementation is highly unpredictable (Roesch-McNally et al., 2018).

4.1.2 Soil health practice adoption

Much of the current conception of farmer behavior change stems from previous models of technology transfer, such as Rogers' diffusion of innovation theory (Rogers, 2003, see Glover, et al., 2019). This theory is commonly used to explain the spread of practices among farmers which can be summarized by visualizing a bell curve, moving over time from early adopters on one end, to the majority in the middle, and finally ending with late adopters, or "laggards" (Rogers, 2003). This model assumes a transactional substitution of existing methods for new, more efficient technology. This model also assumes linear thinking by the farmers that is driven by decisive acceptance or rejection of a technology (Hermans et al., 2021). However, when applied to real agricultural scenarios, which are inherently complex and exist within a broader social, political, and economic framework, the pathway of technology transfer is much harder to understand (Glover et al., 2019). Furthermore, the outcomes of applying technological solutions to agriculture can be shortsighted and may lead to unexpected negative outcomes (Gliessman, 2022; Rust et al., 2022; Warner, 2008).

The term "adoption" is often used in the context of farmer behavior change, Extension work, program evaluation, or to inform research about new agricultural technologies (Glover et al., 2019). Adoption is commonly mischaracterized as a binary descriptor of whether or not a farmer utilizes a new technology or tool, whereas in reality, adoption is a dynamic process with many gradients along a spectrum (Montes de Oca Munguia et al., 2021, 2021). It is also increasingly clear that defining "practice adoption" as a finite goal does not account for the wide array of decision-making farmers are likely to engage in when trying something new: they may be cautious, partially or incompletely implementing a new practice; they may experiment with it; or they may try and then "dis-adopt" it (Montes de Oca Munguia et al., 2021). New scholarship devoted to more holistic understandings of farmer practice adoption has led to the development of nimble frameworks that better account for the reality of change processes (Glover et al., 2019), such as "adoption pathway analysis" (Montes de Oca Munguia et al., 2021; Springer-Heinze et al., 2003).

Many stakeholders seek to motivate farmer behavior change by promoting new technology or practices, which are usually related to improving farm yields, environmental benefits, or both (Eastwood et al., 2017; Pannell & Claassen, 2020). In the context of small-scale diversified farmers, like Vermont vegetable growers, pathways towards practice adoption are even more confounding. Agricultural practices are not discrete, scripted, mobile entities that can be transferred from one setting and implemented in another (Glover et al., 2019). The assumption that a practice could result in similar outcomes across a range of diversified farmers ignores the varying contexts and communities within which small scale farmers exist. Furthermore, many growers innovate their own technologies and share knowledge laterally within their own farming communities (Douthwaite et al., 2003). It is also well established that primary drivers of farmers adoption of new practices is largely based on underlying socio-economic factors such as profitability and social relationships (Bagnall et al., 2020; Hoffman et al., 2014). Identifying these factors within the specific context of Vermont vegetable farms is a critical next step to helping farms adapt and withstand climatic uncertainty.

4.1.3 Agroecosystem resilience

Ecological resilience is a concept first introduced by Holling (1973), defined in simple terms as the ability of an ecosystem to withstand disturbances and recover from a temporary disruption (Holling, 1973). In the years since, this idea has been applied to communities and agroecosystems, particularly in reference to the climate crisis. In the specific context of commercial agriculture, resilience is defined as a farm's ability to survive and maintain production despite agronomic, social, or economic stresses (Tallaksen, 2021). Applied to the broader agroecosystem, resilience is understood as the ability to function in the face of economic, social, environmental and institutional shocks and stresses by adjusting and transforming (Meuwissen et al., 2019). From the perspective of agroecology, resiliency must include adaptivity, and both are critical elements of agroecological transitions (Tittonell, 2020).

4.1.4 Mental models

This study utilizes an approach of co-creating mental models during semi-structured interviews with farmers to better understand what factors influence their soil health decision making (Van Hulst, 2020; Pager & Curfs, 2016). A mental model is a conceptual map of the interconnected elements that exist in an individual's mind, based on experiences, culture, values, and beliefs. Mental models can help visualize complex factors and reveal assumptions that inform farmers' behavior, such as social, environmental, personal, or political factors (Moon et al. 2019; Van Hulst, 2020). In past studies, mental models have been successfully used to explain decisions of farmers because they help reveal how people interact with complex ecosystems (Prager and

Curfs, 2016). Educators or Extension professionals are more likely to succeed in helping farmers develop new practices or adopt new knowledge using mental models (Eckert and Bell, 2009). In this context of examining soil health perceptions, mental models are well-suited to reveal underlying behaviors that impact the adoption of soil health practices on Vermont vegetable farms (Moon et al. 2019; Jones et al. 2011; van Hulst et al. 2020; Prager & Curfs 2016).

The use of mental models aligns with agroecological approaches, specifically they reduce communication barriers between service providers (e.g., Extension and other professionals who provide services and education to agricultural communities) and farmers (Horner, 2023; van Hulst et al., 2020). The principles of agroecology seek to elevate farmer expertise, encouraging researchers to co-create knowledge while honoring local culture and traditions (Caswell et al., 2021; FAO, 2019; Wezel et al., 2020). Mental models support these aspects of agroecology by validating local farmers' knowledge and insuring that soil conservation practices align with local cultural context (Halbrendt et al., 2014). Examples exist in the literature of the application of mental models to support agroecological approaches, such as biological pest control (Bardenhagen et al., 2020) and ecological weed management (Jabbour et al., 2014).

Although mental models are specifically useful for identifying the context within which an individual makes decisions, they can also be used to capture collective knowledge from a specific group, which may help articulate a shared pathway towards lasting socio-ecological outcomes (Halbrendt et al., 2014). Compiling a group mental model helps reveal a set of knowledge specific to a community and cultural context

(Hoffman et al., 2014). It is well known that farmer soil health practices are far from homogeneous (Carlisle et al., 2022); therefore creating a mental model within a small group of local farmers can help reveal certain region-specific soil health approaches. Making grouped mental models explicit and sharing them can also help build co-creation of knowledge and expanded group thinking (Utter et al., 2021). Visual representations of grouped mental models can also create a shared vision among a group of farmers, providing a mechanism to advocate for context specific needs (Horner, 2023; Moon et al., 2019).

4.1.5 Role of Extension

Various types of Extension services exist worldwide, offering a range of services that includes farm visits, technical assistance, farm viability support, and scientific research. In the U.S., Extension programs are housed in land grant universities, most of which were founded through either the Morrill Act of 1862, Smith-Lever Act of 1914 (Suvedi & Kaplowitz, 2016), or the Equity in Educational Land-Grant Status Act of 1994. It is important to pause here to acknowledge the terrible history associated with land grants that includes land permanently stolen from Native Americans (Lee & Ahtone, 2020).

Most Extension programs have evolved over time from a hierarchical, science-based approach (often referred to as technology transfer) to a more participatory approach (Allan et al., 2022; Suvedi & Kaplowitz, 2016). Many Extension specialists now focus on peer to peer learning and implement more collaborative models of information transfer (Birkhaeuser et al., 1991; Pan, 2014). Numerous examples exist in the literature detailing successful alliance between Extension growers alliances, resulting in some cases in the development of agroecological knowledge and positive environmental outcomes (Dlott et al., 1994; Warner, 2008).

While research has examined farmer behavior change and how it relates to Extension support (Horner, 2023; Schattman et al., 2018), it is also important to trace the intent to implement practices and the actual agronomic and environmental outcomes (Kuehne et al., 2017). Researchers offer many different explanations for the broad array of social, economic, political, and personal factors that influence farmer decision making. One specific effort made to explore mental models through Extension was made by Eckert and Bell in 2005, noting that “Agricultural educators who seek to promote the success of small farm operators need to understand the mental models of farming held by farmers with whom they work” (Eckert & Bell, 2005, p.2). While previous research shows that barriers to implementation may vary based on farmers’ situations, such as location, markets, resources, climate (Baumgart-Getz et al., 2012), this project seeks to gain a more holistic understanding of what factors impact Vermont vegetable farmers’ soil health practices and how Extension can better support these farmers.

4.2 Research questions

This chapter explores the factors that enable or limit soil health practice adoption on Vermont vegetable farms, utilizing mental models co-created with farmers as a tool for investigating my overarching research questions: What unique socio-ecological factors are specifically identified by vegetable farmers that support and/or inhibit the adoption of soil health practices? Are there common barriers within this small group of farmers that can be identified and addressed?

Applying an expansive agroecological approach to these issues promises to further reveal the web of factors driving farmer practices, including farmer knowledge, social networks, policy, local governance, farm economics and farmer practice implementation. Revealing these connections in the specific circumstances of diversified vegetable growers is critical to supporting improved outcomes for both the farmers and the environment.

4.3. Methods

My colleague C. Horner (UVM PhD, 2023) and I conducted research in the spring of 2022 to better understand farmer and Extension provider approaches to soil health, specifically their constraining and enabling factors. C. Horner has published her findings, complementary to those shared in this chapter, in “Exploring Potential Domains of Agroecological Transformation in the United States” (Horner, 2023). To answer our respective research questions, we followed methods from Van Hulst et al. (2020) to co-construct mental models with participant farmers. Below is a description of our methods following the Tong et al. 32-item checklist (Tong et al., 2007).

4.3.1 Domain 1: Research team and reflexivity

Our research team consisted of C. Horner and myself. A. Gerlicz (UVM PhD student) was hired as a research assistant for conducting the interviews. C. Horner and I led the majority of the interviews while A. Gerlicz and either C. Horner or I drafted the mental models, took notes, and asked clarifying questions.

Participants were recruited for this project with an email explaining research goals, funding source, describing the research team, outlining the process, time commitments, dates, and paid compensation for participation. This project, including methods and recruitment strategies, received approval from the IRB approval at the University of Vermont. At the start of each interview, introductions were made to the research team, briefly describing backgrounds, interest in the topic, and research objectives. Participants were assured of the confidentiality of the interviews and asked if recording for the purposes of later transcription was acceptable. Interviewees had the opportunity throughout the process to skip questions or ask more about the interviewers' personal background in the topic (Horner, 2023). Interview protocols and guiding questions are available in Appendix A.

4.3.2 Domain 2: Study Design

It is important to reveal the broader theoretical framework of this study to convey my values and the goal of how the knowledge created through this research will be used (Collins & Stockton, 2018). The theoretical basis of mental models was formulated by cognitive psychologists to describe the way people apply their background knowledge and make inferences about situations before acting (Johnson-Laird 1980 as cited in Vuillot et al., 2016). Mental models have had various definitions and been used in many ways, leaving no uniting theoretical frameworks for their use (van Hulst et al., 2020). In this research project, we used a semantic web analysis to visualize the farmer's mental models with regards to soil health (Prager & Curfs, 2016).

4.3.3 Theoretical background

Before describing the process of co-constructing mental models, I believe that as a researcher, I need to be reflexive and disclose what assumptions I personally bring to this work. As a researcher and University of Vermont Extension employee, I am aware of the relative income and job security I have while discussing fundamental stresses facing farmers. At the same time, through my career as a farmer, I have experienced some of the same social, family, economic, and agricultural concerns as some of the interviewees. My life experiences and the close relationships I have with some of the participants undoubtedly shaped how I conducted the interviews and analyzed the information. My overall approach to this research is with a lens of "critical paradigm", which posits that as a researcher, I aim to uncover hidden assumptions based on social, political, cultural scenarios. This approach can be achieved by collaboration with the participants and iteratively checking in with the farmers throughout the process (Creswell & Miller, 2000).

4.3.4 Theoretical framework

The discipline of agroecology provides a useful lens for understanding the broad scope of factors involved in farmer adoption of soil health practices. In contrast to applying a purely agronomic approach, an agroecological framework incorporates social and ecological factors alongside the biophysical. This enables a comprehensive understanding of the interconnected influences on farmer behavior and subsequently, on soil health outcomes. Scholars of agroecology recognize that many of the barriers farmers face are beyond the farm scale, and therefore must be addressed through shifts in political and economic power (Anderson et al., 2019).

Utilizing the discipline of agroecology to understand soil health on vegetable farms offers a flexible approach that centers farmer knowledge and honors the complexity of ecosystems, communities, and the socio-political spheres. This framework also offers tools to bridge gaps between practice adoption and long-term resiliency. An agroecological view suggests that practice adoption ought to be viewed as a dynamic process, with practices that can be partial, incomplete, or experimental (Montes de Oca Munguia et al., 2021; Pannell & Claassen, 2020). It is arguable that farmer adoption behavior, can support agroecological transitions and farm resiliency (Tittonell, 2020). In this way, agroecology enables a deeper understanding of the research on practice adoption, offering an explanatory framework about how multiple factors influence farmer behavior and ultimately, the agroecosystem.

4.3.5 Participant selection

We recruited 34 farmers for the study, utilizing purposive sampling (Tongco, 2007) to interview farmers managing vegetable and berry; dairy; and non-dairy livestock operations. Within these farm types, we tried to recruit even numbers of organic and non-organic farmers to represent the range of approaches. For the purposes of my research, I only utilized data from the twelve vegetable and berry farmers as well as their two grouped mental models. For more information on participant recruitment for all the interviews, as well results and analysis, see C. Horner’s work (Horner, 2023).

4.3.6 Data collection and mental model co-creation

An interview guide was developed ahead of time by C. Horner and me. It was pilot tested on a non-participant vegetable farmer who offered constructive feedback. Due to the Covid-19 pandemic, all interviews except two were conducted remotely using Zoom. A semantic web approach based on van Hulst et al. (2020) was used to capture concepts during the interview using Lucidspark (© 2023 Lucid Software Inc.) a web-based software that enabled concept sorting and shared screen displays. This technique uses concepts as described by farmers linked with arrows that are often annotated with descriptive verbs or adjectives.

Interviews were approximately one hour in length, with 45 minutes of that time allocated to conversation, and the final 15 minutes available to visually share and co-construct the farmer's mental model. This process of co-creating mental models enabled identification of many social and ecological factors that shape understandings and management of soil health. After the interviews, the mental models were edited for visual clarity by the research team and shared back via email with interviewees for additional feedback (Horner, 2023). The interview guide is included in Appendix A.

4.3.7 Creating grouped mental models

We created grouped mental models for organic vegetable farmers (n=7) and non-organic vegetable farmers (n=5). These models included concepts and practices mentioned by a majority (>/= 50%) of individuals in a group. This process involved iterative comparisons using visual displays and arrays which enabled identification of common concepts. Grouped mental models were shared with individuals in each group.

We then conducted focus groups separately for organic and non-organic vegetable growers to elicit feedback on each of the grouped mental models. Focus groups provided an opportunity for participatory analysis and broader conversation comparting soil health practices (van Hulst et al., 2020).

Farmers were offered hourly compensation for participating in both the individual interview and focus group. This acknowledged the expertise of farmers and reduced the burden of participating in research (Horner, 2023).

4.3.8 Data Analysis

For this chapter, only the vegetable farm interviews were used (n=13). These interviews were transcribed by two services, Otter ai (Okta, 2022) and goTranscript (2022) and loaded in NVivo 1.3 (QSR International, 1999-2020). The transcripts were open coded during multiple readings using an iterative, inductive approach. (Braun & Clarke, 2006; Carlisle et al., 2022; Horner, 2023; Vollstedt & Rezat, 2019). Following the six-phase procedure outlined in Braun and Clarke (2006), key concepts were first identified and then used to develop codes. The codes were then used to identify broader themes, where were then refined and compared to the visual mental models and relevant literature (Braun & Clarke, 2006; Creswell & Miller, 2000; Horner, 2023; Vollstedt & Rezat, 2019). The fifteen-point checklist in Braun and Clark (2006) helped guide the process of transforming raw data using thematic analysis.

4.4 Results

To organize the results of the mental models and interviews, I begin by identifying themes that emerged when farmers described soil health practices such as “financial constraints”, “farmer to farmer knowledge”, and “ecosystem and the environment”. First, I describe farm context based on the interviews; second, I compare their general philosophies towards soil health. Finally, I sort the data into two broad categories within which farmers describe adoption of soil health practices, “enabling factors” and “constraining factors”. For each of these categories, clear themes emerged in the way farmers describe their relationship with soil health practices. Examples of individual mental models from one organic farmer and one non-organic farmer are displayed in Figures 10 and 11. Grouped mental models of organic and non-organic farmers are in Figures 12 and 13.

4.4.1 Farm context

Prior to co-constructing mental models, farmers were asked for a short description of their farms and businesses, which offers important context for the data collected. All farmers (12/12) own the land they farm on; three of the farmers have farmed the same piece of property for >35 years; four have been on land 10-15 years, and the remaining five have been on their farm for less than ten years. Seven of the farms are certified organic by Vermont Organic Farmers (VOF) and five are not organic. Scale is an important factor when examining soil health practices. In this study, 7/12 farmers grew on 8 acres or less and operated with a combination of tractor and hand labor. The remaining 5/12 farms have 25-50 acres in vegetables and are highly mechanized. Farmers were not asked to disclose any financial information. Farm characteristics are summarized below in Table 10.

Table 10: Farm characteristics

Farm ID	Soil texture	Est. acres in vegetables	Est. years owning farm	Certified organic?	Primary markets
1	sandy loam	50	10	OG	wholesale/ farmers market
2	loam	5	10	OG	CSA
3	sand & clay	5	17	OG	CSA/ wholesale
4	loam	5	7	OG	CSA/ wholesale
5	loam	5	8	OG	CSA/ farmers market
6	loam	25	6	OG	farm store/ wholesale
7	sandy loam	5	4	OG	CSA/ wholesale/ farm store
8	loam	4	2	Not OG	wholesale
9	sandy loam	25	35	Not OG	farm store/ wholesale
10	sandy loam	40	40	Not OG	farm store/ wholesale
11	loam	4	12	Not OG	CSA/ farm store
12	sandy loam	50	35	Not OG	wholesale/ farm store/ CSA

[1] CSA = community support agriculture farm
[2] OG = certified organic farm
[3] Not OG = not certified organic

4.4.2 Soil health philosophy

Growers expressed a wide range of sentiments about soil health, from purely mechanistic understandings of soil chemistry to more integrative descriptions of the soil ecosystem. The farmers with less than 15 years on their land) (n=8 spoke) of soil as the most valuable resource on the farm; one farmer routinely shares her reverence for the soil with her employees: “I preach that like, you know, soil is number one, and we do whatever we can to take care of it.” Another farmer echoed this,

> “You can't skimp on the soil, [if you do], you're not going to get anything…none of the other triangles of the pie chart are going to work out. You can reuse boxes and…buy a used car instead or a new one…but if you're not taking care of the soil it's not going to work.” (Farm ID 4)

In contrast, the growers with longer land tenure (>15 years, n=4) drew a direct and practical connection between soil health and farm outcomes without questioning broader ecological concerns:

> “Well, for us to it all starts with soil health. And…that's how the business operates. If we have healthy soil, then we're growing healthy vegetables that we're selling to our customers. And in theory, they'll have those vegetables and they'll be like, wow, these taste good, they look good. There's just something more energetically viable about them. Because they're coming from healthy soil.” (Farm ID 3)

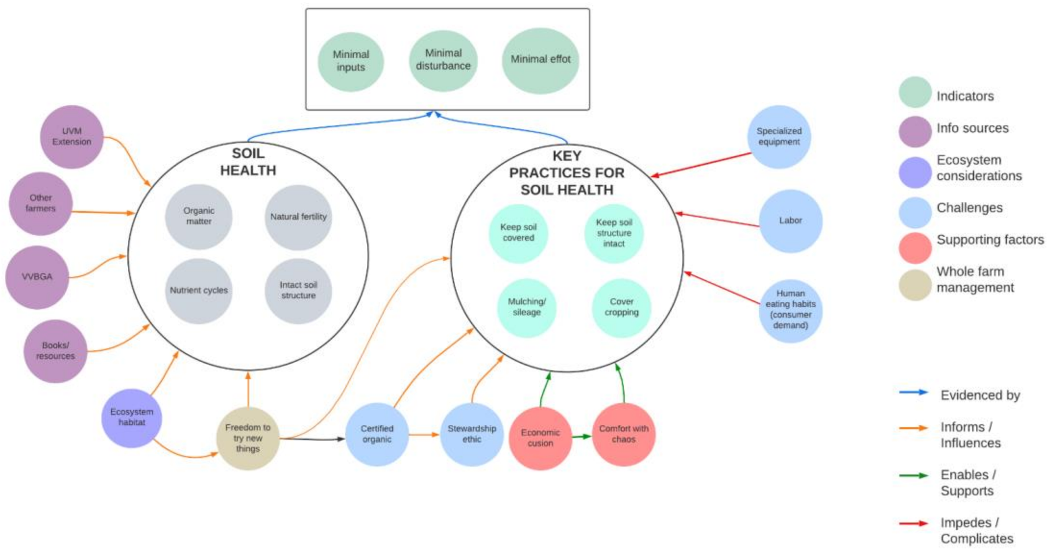

Figure 10: This is an example of an organic vegetable farmer’s mental model of soil health co-created during an elicitation interview. Colors were used to group factors thematically and lines were color-coded to describe connections.

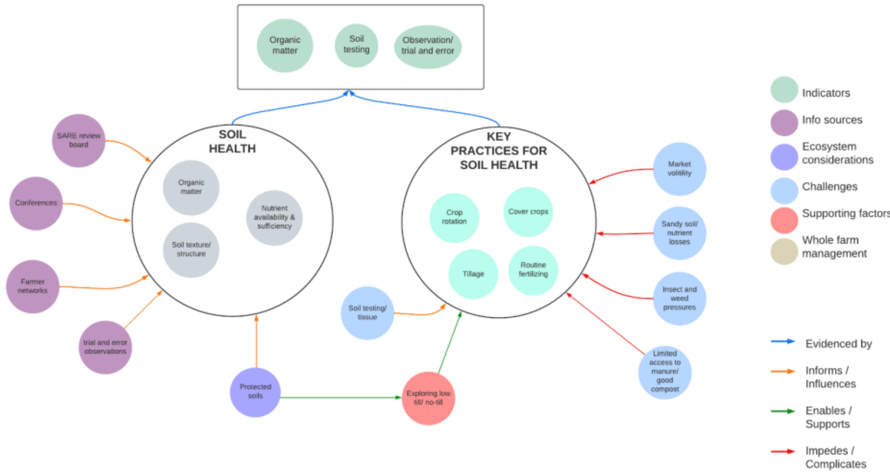

Figure 11: This is an example of a non-organic vegetable farmer's mental model of soil health co-created during an elicitation interview. Colors were used to group factors thematically and lines were color-coded to describe connections.

4.4.3 Comparing organic and non-organic grouped mental models

While there are many similar pathways when comparing grouped organic with non-organic ("conventional") mental models, a few distinctions emerged. The non-organic farmers focused on soil heath that is largely governed by an input-output approach. They were more likely to equate organic matter and nutrients with soil health, focusing on cover cropping as a key soil health practice. These farmers looked to farm equipment and soil tests as their primary soil management tools. It is also important to note that all three of these farmers dramatically decreased chemical use over the course of the last several decades in recognition that the soil health was suffering and "there was nothing nice about it." In their mental models, these farmers also noted that they also became early adopters of cover crops and experimented with reduced tillage practices. Their mental models reflected a desire to continue learning and exploring practical applications of soil health in direct connection to organic matter, tillage, and cover crop cropping.

Figure 12: This is a grouped mental of the 5 non-organic vegetable farmers interviewed. The groupings were created by combining the individual mental models. The colors of the boxes were used to capture themes and arrows were colored coded to show influences. This figure was shared during the focus group.

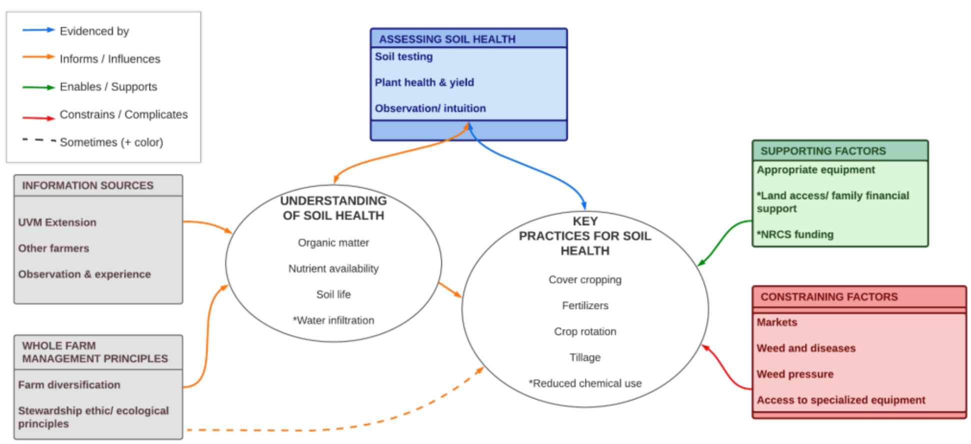

Figure 13: This is a grouped mental of the 7 organic vegetable farmers interviewed. The groupings were created by combining the individual mental models. The colors of the boxes were used to capture themes and arrows were colored coded to show influences. This figure was shared during the focus group.

In comparison, the organic farmers (7/12) described broader, holistic approaches to soil health within the context of supporting the ecosystem. For example, one farmer invests in wildlife habitat on the farm:

> "We have a lot of birds, a lot of songbirds. We're starting what we're calling the bird program this year…we're gonna put nesting houses along our deer fence and we've been doing pollinator strips of wild flowers…birds and bugs, you know, we try to make habitats for them." (Farm ID 6)

Another farmer spoke of grappling to balance a holistic, nature-based approach with production realities, viewing soil management as potentially in conflict with the natural ecosystem:

> "I think it would be just safe to say that I was very romantic...in the beginning thinking [that] you farm and make a living in…harmony with the soil…I don't believe that's true anymore…which is a hard thing to admit to yourself when you're a farmer, and when you get into farming to save the Earth, right, like a lot of us do." (Farm ID 8)

4.4.3 Enabling factors

In this section, themes that emerged as enabling factors for soil health practice implementation are described below. Figure 14 illustrates the enabling factors extracted from farmer mental models.

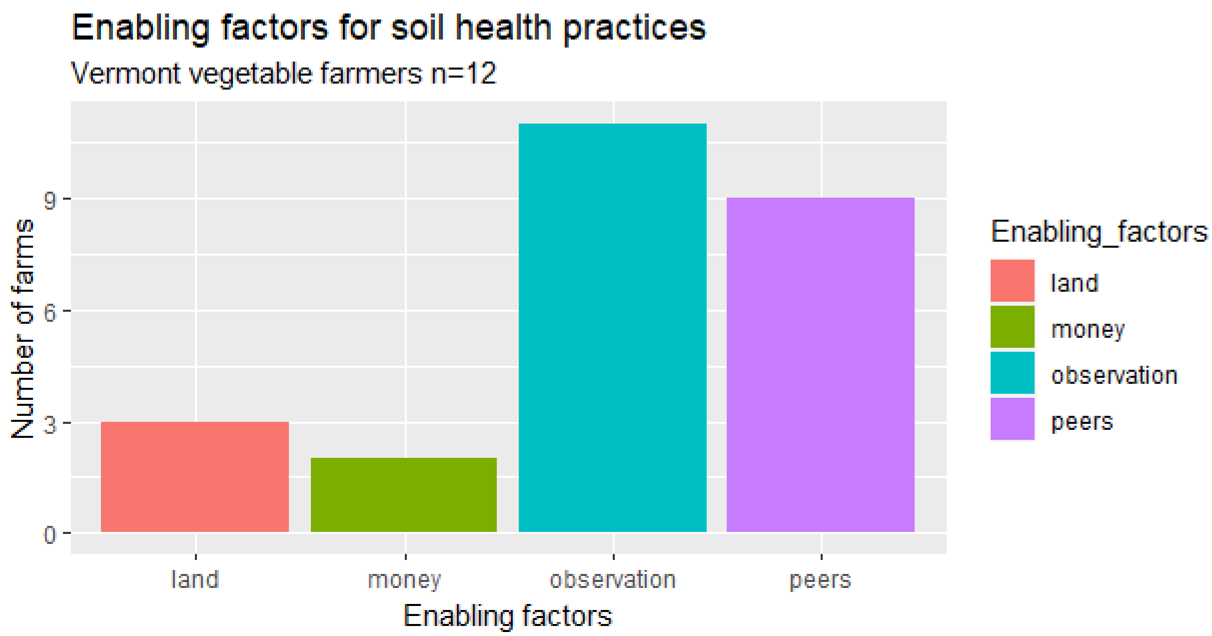

Figure 14: Enabling factors to soil health practice adoption. This chart summarizes interview coding results showing the number of farmers who talk about each factor.

4.4.3.2 Observations and intuition

All but one of the vegetable farmers (11/12) emphasized their own power of observation as the most prevalent factor that allows them to understand and implement soil health practices. One vegetable grower who has grown for 30 years on the same land said, “I can tell you the fields where I'm going to have a problem.” Another farmer described observation as “the greatest teacher,” while another noted that it allowed him to make quick, intuitive decisions about soil health simply by “paying attention to what's happening.” Several farmers made a point of mentioning that alongside observation, they enjoyed innovating, experimenting, and are “voracious learners”. However, one farmer cautioned against elevating farmer knowledge and making decisions based solely on observation; he advocated instead for more outside support to provide necessary information:

> “We don't know [what] we don't know…basically everything I've told you so far, I made it up. And it needs to be challenged. And I think that's the struggle of the farmer…we are left to make things up based upon what we see... But having [new] information is…what farmers need.” (Farm ID 1)

4.4.3.3 Learning from other farmers and innovation

The strong network of vegetable growers in Vermont emerged from the interviews as the second most impactful factor in farmer mental models. Ten out of twelve farmers expressed deep appreciation for the Vermont community of growers, the Vermont Vegetable and Berry Growers Association (VVBGA), and UVM Extension. Growers especially noted the VVBGA listserv, which has approximately 800 members, with posts covering a wide range of topics. The oldest farmer in this project mentioned the change in communication he has witnessed; when he started 40 years ago, everyone was “reinventing the wheel in their own little valley with very little communication, and now… this tremendous amount of information sharing going on through the listserv, which is an enormous difference.”

Farmers also strongly noted the value of learning from the experimentation and innovation of other growers. In farmer mental models, there are many connections drawn between practice adoption and innovative practices developed by Vermont farmers. Innovation was strongly connected to knowledge sharing both in the interviews and mental models. For example, one farmer talked about how he circumvented the expense of purchasing a no-till transplanter by fabricating his own equipment based on the advice from other growers.

4.4.4 Factors that both constrain and enable

Several of the themes that emerged in mental model co-construction related to resource access and are therefore described by some farmers as enabling and by others as limiting.

4.4.4.1 Money

All but one (11/12) of the farmers drew strong connections between financial resources and soil health practices. One farmer spoke of his ability to develop innovative soil health practices as directly linked to financial comfort, “I think there's some people who really come into farming without any money…I've had financial backing...so I don't feel like if I lose a crop that I'm going to have to sell the farm. That allows a fair amount of freedom.” This same farmer also connected his economic freedom to a “comfort with chaos” on his mental model; because he doesn’t fully depend on the revenue generated by the farm, he can experiment and accept some failures.

For the majority of the farmers, however, financial limitations were the number one constraint listed by growers as a barrier to soil health practices (9/12), linking money to nearly every other barrier they mentioned (such as labor, equipment, land, etc.). Money limited investments farmers were able to make towards farm soil health, including purchases of innovative equipment such as reduced till grain drills or roller crimpers. Production pressures force farmers to make difficult choices between farm financial health and soil health, “there's sort of a financial thing…planting enough stuff to pay the bills but also trying to take care of your soil” (Farm ID 5). One grower bluntly put money at the base of all soil health issues:

> "I think sadly, in some ways, what influences our relationship with the soil is money. And I say that…everything we would want to do…to build our soil…just requires more time, more labor, more economic inputs." (Farm ID 1)

This farmer also noted that if he had more financial resources, he would dedicate a skilled worker to focus on soil health.

4.4.4.2 Access to land

Land was noted as a fundamental resource for soil health practices (n=10). Farmers who identified land as an enabling factors (n=3) indicated that access to a roughly even proportion of cash crop to cover cropped land was pivotal in enabling soil health improvements, specifically related to cover cropping and crop rotations. As one grower said, "I mean, it's a luxury to be able to grow on a new field every year." Growers also noted that having extra land allowed them to experiment and innovate new practices.

In contrast, not having enough land, poor soil, or challenging topography were all cited as issues that limited some farmers' (8/12) ability to implement soil health practices. The majority of farmers in this study clearly spoke about feeling "really torn" between wanting to take land out of production for cover cropping but needing income from a cash crop. As one farmer said, "you'd be interested in taking more land out of production to let it rest…because that might be great for soil health, but you really still need that land base to be making enough money to survive." Many of the farmers emphasized the limitation land placed on both their businesses and their soil health, as one said, "I think my biggest limitation is land base…the ultimate would be if I had an additional 10 acres to just cover crop and let rest every year."

However, one farmer noted the reality of production pressures even after he acquired more land with the goal of improving soil health practices; he "just…scaled up production under the wholesale vegetable side of things." This reflects a common tendency; as another farmer put it "to …expand our business to basically, you know, fill out the land that we do have."

All the farmers on recently purchased farms (n=5) made specific connections between the limitations of farming new land and the expense of building up soil health to meet production needs. This burden of generating income from previously degraded land is clearly linked to the financial pressure famers face, especially in the first years on new land.

> "When we first started, we had old hay fields that have been mined for nutrients for years and we didn't have a whole lot of money to spend on fertilizer. So, we were struggling the first three to four years just trying to get our nutrients up." (Farm ID 6)

Others echoed this experience, describing incredibly degraded land due to previous hay or corn production. These farmers described an expensive, years long process to rebuild the basic nutrient balance of the soil to support vegetable cash crop production.

4.4.5 Constraining factors

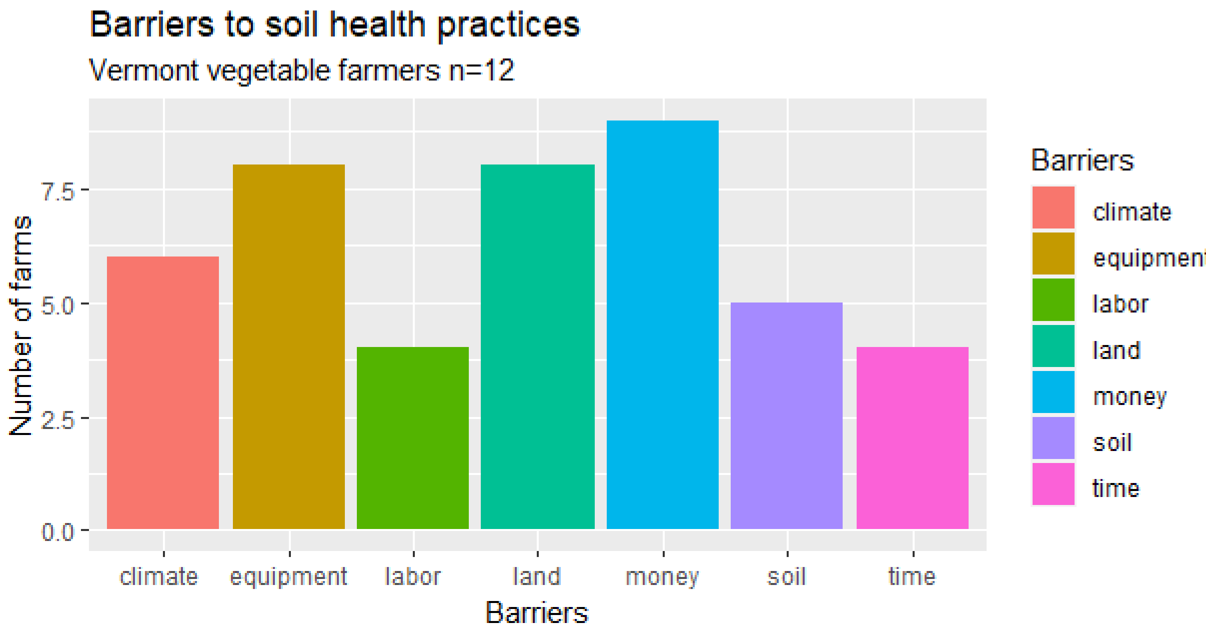

Figure 15: Disability factors to soil health practice adoption. This chart summarizes interview code results showing the number of farmers who talk about each factor.

4.4.5.1 Equipment

Farmers list appropriate equipment as a significant limitation in soil health practices (8/12). Some farmers described non-existent technological innovations specifically suited to their farm production that could change their approach to soil health ("impossibly expensive things"). Others looked towards small practical improvements ("better equipment might be helpful"). Some farmers knew exactly what equipment would help but were limited by money, whereas another farmer in the group who had experimented with borrowed soil health equipment concluded that the equipment is just too expensive: "we've been experimenting a lot with no till over the last couple of years and we've spent some money on it. And we're not…going that route because of the [cost of] machinery."

4.4.5.2 Climate change

The vulnerability farmers experienced due to climate change was addressed by half of the farmers (6/12) interviewed, although they were not asked directly about it. In their mental models, these farmers linked soil health practices closely with climate change, as both a mechanism to build resiliency as well as a source of uncertainty regarding their ability to implement soil health practices during times of climate disruption. Farmers also cited climate change and extreme weather as disruptive to their regular patterns of soil health practices, such as fall cover crop seeding. In some cases, extreme weather was not only disruptive, but forced farmers to implement poor soil health practices: "I think that rain…had a bad effect last year on our soil biology and structures [because] we had to work things wetter than we would have liked." (Farm ID 10) Of major concern were crop losses associated with climate change:

> "I mean, certainly, the extremes of weather aren't helping…we are seeing crop loss [due] to standing water which is just devastating… We've been [at] the tipping point [of] our ability to continue to do what we do and that's sort of …living with a huge amount of anxiety in the face of…the environmental issues." (Farm ID 1)

4.4.5.3 Labor

A subset of farmers who participated in this study (5/12) connected labor issues as an impediment to soil health practices. Managing labor absorbed a disproportionate amount of farmers' time and caused one farmer to conclude that "biggest burnout point in the season is labor management." Another referred to managing labor as "a time drain" while another noted that time spent supervising a crew pulled him away from focusing on soil health practices. Finally, two farmers mentioned that soil health practices impacted the attitudes of farm workers. One of these farmers described how discouraged his crew was after trying to rescue a failed with no-till sweet corn crop: “you can say the proof is in the pudding when they…[gave] me a dirty look. Not so good. [We won’t try] that again.”

4.4.5.4 Time

The final limitation that farmers linked to soil health practices was time, in terms of physical ability to implement practices and management capacity. As one farmer said, “So if you asked me what we need: time, time, every day, time, time…every practice just requires more time.” Another farmer emphasized the frenetic energy of the growing season as a big limitation for her ability to pay attention to soil health: “The momentum of the season is happening...I know the consequences [to soil health] are going to be shitty, but I'm not putting the brakes on. That really sucks.” Some farmers mentioned time as limiting their ability to source information, visit other farms, and acquire knowledge about soil health; one farmer specifically noted that this is where she could use help from outside resources, like Extension.

4.5 Discussion

Below, I discuss how the information synthesized from this project affirmed what previous literature has already demonstrated: soil health practices are often limited by socio-economic factors (Prager et al., 2011; van Hulst et al., 2020). Furthermore, these findings support previous research revealing that farmer decision making about soil health is intricately related to multiple factors, and therefore not always predictable (Prokopy et al., 2019). Finally, these results strengthen a call for revised Extension approaches to motivating farmers practice “adoption”.

Although this study represented a small sample size of vegetable farms, the heterogeneity of the mental models illustrates the wide range of scale, social factors, and economic status that exists within the Vermont vegetable farm community, affirming other findings that farmers and farms are deeply unique and that practices must be considered within their specific context. (Carlisle, 2016; Prager & Curfs, 2016).

While the themes distilled in the results section reflect some common needs for all farmers, there is no single mechanism that would facilitate soil health improvements on all twelve of the farms interviewed. This is evidenced by the diverse responses farmers offered to describe their primary limitations, which range across the spectrum of physical (land), social (labor), and global (climate change). In this study, farmers described barriers that have also been found in other studies around the U.S., including land limitations that impede soil health practices such as cover cropping and crop rotation (Carlisle, 2016; Carlisle et al., 2022; DeVincentis et al., 2020; Schipanski et al., 2014; Snapp et al., 2015; Snapp et al., 2005). The connections revealed in these results between practice adoption, land, and access to appropriate equipment are also well documented in other literature as significant barriers to soil health practice adoption (Carlisle et al., 2022; S. S. Snapp et al., 2005). Despite the many barriers farmers experience, this study also validated the depth of peer to peer learning taking place among farmers, which has also been found in multiple other studies (Carlisle, 2016; Douthwaite et al., 2003; Eckert & Bell, 2005; McAllister & Bell, 2021).

Even among the diverse needs expressed by farmers, the results demonstrated several trends that emerged in the grouped mental models, which provide a useful mechanism to find common ground among farmers, to identify structural barriers, and to inform future policy development (van Hulst et al., 2020). The value of grouped mental models is also apparent when comparing the two subsets of farmers interviewed for this study, organic and non-organic (conventional) vegetable growers. The results aligned with compared mental models in van Hulst et al. (2020), in which farmers interviewed described their practices without labelling them as “organic” or “conventional”. Similarly, the results from this work demonstrated that farmers do not identify their soil health practices within a certain discipline. Instead, these findings revealed that all the farmers approach soil health from various points along a holistic spectrum. This finding is similar to a use of mental models to examine biological insect control for both organic and conventional farmers, which demonstrated that although there were differences between the two approaches, both organic and conventional farmers struggled with the same barriers (Bardenhagen et al., 2020). Likewise, in this study, the similarity of barriers identified by both organic and non-organic farmers suggested that vegetable farming in Vermont could be considered a unique cultural subset of farming. However, there are some distinctions noted between the two groups in this study, which point to more subtle understandings of the leverage points for soil health management. As described in the results section, this study found that although conventional growers viewed soil health within an ecological framework, the management practices they identified specifically addressed inputs and outputs. In comparison, organic farmers focused more on the ecosystem and practices they employed to support it.

This study affirms that co-constructing a mental model can help reveal farmers' values and beliefs, what guides their decisions, and their current framework for making farm decisions (Eckert & Bell, 2005). This information helps both the Extension person and the farmer understand what drives decisions and what can be tweaked. This research also affirms that practice adoption is not a binary action; farmers described many levels of experimentation, partial adoption, and dis-adoption, well illustrating what scholars have described as a dynamic pathway towards practice adoption (Hermans et al., 2021; Montes de Oca Munguia et al., 2021; Pannell & Claassen, 2020).

These findings align with others to reject the binary and linear models of practice adoption that continue to inform Extension program development and evaluation (Gliessman, 2022; Springer-Heinze et al., 2003; Warner, 2008). As described in the introduction, there are significant resources in the U.S. and in Vermont dedicated to motivating farmer implementation of soil health practices. However, the findings in this study demonstrate that farmer adoption is not inhibited by lack of access to programs, inadequate knowledge, or by a lack of care for the agroecosystem. Instead, this study refutes the idea that farmers need additional assistance focused on soil health, and instead suggests that farmers need support addressing other barriers. Shifting technical support to relieve farmers of some of the pressures imposed upon them by other barriers could enable farmers to actually act on the knowledge they already possess.

4.6 Conclusion

This work provides a diversity of information that can be used to inform future support for farmers, especially the subjects of this research, Vermont vegetable farmers.

First and foremost, this project supports the benefits of Extension personnel utilizing a mental models approach in advance of technical assistance. This process is not time intensive and could result in increased alignment between Extension and farmers. Understanding the underlying mechanisms of farmer behavior would save time and resources that may otherwise be spent trying to address factors that are unrelated or do not exist. Furthermore, co-constructing mental models with farmers allows them to articulate and visualize their motivations, which can empower them to adjust practices without any assistance. Finally grouped mental models are a potential step towards advocacy for groups that do not usually identify as having cohesive needs that could be addressed at a program or policy level.

This study also investigates important questions related to both the support offered to farmers through Extension outreach and the outcomes from this work and confirms that an approach to soil health technical assistance that accounts for social and economic context could result in more lasting and meaningful outcomes. Restructuring Extension approaches would not be simple, but these findings provide context for understanding where and how improvements can be made. This work also suggests that a simple first step involves shifting the conceptualization of practice adoption away from a linear approach with a finite end and instead developing mechanisms that are focused on outcomes rather than practices.

Finally, this research reflects the breadth and depth of knowledge Vermont vegetable farmers bring to their work, the generosity with which they share it, and the agroecological view they embrace. These growers persist in the face of the many challenges articulated here, growing healthy food for their communities, and stewarding the agroecosystem.

4.7 References

Allan, C., Cooke, P., Higgins, V., Leith, P., Bryant, M., & Cockfield, G. (2022). Adoption; a relevant concept for agricultural land management in the 21 century? *Outlook on Agriculture*, *51*(4), 375–383. https://doi.org/10.1177/00307270221126540

Anderson, C. R., Bruil, J., Chappell, M. J., Kiss, C., & Pimbert, M. P. (2019). From Transition to Domains of Transformation: Getting to Sustainable and Just Food Systems through Agroecology. *Sustainability*, *11*(19), Article 19. https://doi.org/10.3390/su11195272

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

Bardenhagen, C. J., Howard, P. H., & Gray, S. A. (2020). Farmer Mental Models of Biological Pest Control: Associations With Adoption of Conservation Practices in Blueberry and Cherry Orchards. *Frontiers in Sustainable Food Systems*, *4*, 54. https://doi.org/10.3389/fsufs.2020.00054

Baumgart-Getz, A., Prokopy, L. S., & Floress, K. (2012). Why farmers adopt best management practice in the United States: A meta-analysis of the adoption literature. *Journal of Environmental Management*, *96*(1), 17–25. https://doi.org/10.1016/j.jenvman.2011.10.006

Baumgartner, J. A. (2016). *Biodiversity Continuum Chart*. Wild Farm Alliance. https://www.wildfarmalliance.org/biodiversity_continuum_chart

Biardeau, L., Crebbin-Coates, R., Keerati, R., Litke, S., & Rodríguez, H. (2016). *Soil Health and Carbon Sequestration in US Croplands: A Policy Analysis Prepared for: Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture (USDA) and the Berkeley Food Institute (BFI)*.

Birkhaeuser, D., Evenson, R. E., & Feder, G. (1991). The Economic Impact of Agricultural Extension: A Review. In *Source: Economic Development and Cultural Change* (Vol. 39, Issue 3).

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

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

Carlisle, L., Esquivel, K., Baur, P., Ichikawa, N. F., Olimpi, E. M., Ory, J., Waterhouse, H., Iles, A., Karp, D. S., Kremen, C., & Bowles, T. M. (2022). Organic farmers face persistent barriers to adopting diversification practices in California's Central Coast. *Agroecology and Sustainable Food Systems*, *46*(8), 1145–1172. https://doi.org/10.1080/21683565.2022.2104420

Caswell, M., Maden, R., McCune, N., Mendez, V., Bucini, G., Anderzen, J., Izzo, V., Hurley, S. E., Gould, R. K., Faulkner, J. W., & Juncos-Gautier, M. (2021). Amplifying Agroecology in Vermont: Principles and Processes to Foster Food Systems Sustainability. *USDA Agricultural Research Service (ARS) Center*. https://scholarworks.uvm.edu/arsfoodsystems/4

Collins, C. S., & Stockton, C. M. (2018). The Central Role of Theory in Qualitative Research. *International Journal of Qualitative Methods*, *17*(1), 1609406918797475. https://doi.org/10.1177/1609406918797475

Creswell, J. W., & Miller, D. L. (2000). Determining Validity in Qualitative Inquiry. *Theory Into Practice*, *39*(3), 124–130. https://doi.org/10.1207/s15430421tip3903_2

DeVincentis, A. J., Solis, S. S., Bruno, E. M., Leavitt, A., Gomes, A., Rice, S., & Zaccaria, D. (2020). Using cost-benefit analysis to understand adoption of winter cover cropping in California's specialty crop systems. *Journal of Environmental Management*, *261*, 110205. https://doi.org/10.1016/j.jenvman.2020.110205

Dlott, J. W., Altieri, M. A., & Masumoto, M. (1994). Exploring the theory and practice of participatory research in US sustainable agriculture: A case study in insect pest management. *Agriculture and Human Values*, *11*(2), 126–139. https://doi.org/10.1007/BF01530453

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

Douthwaite, B., Kuby, T., van de Fliert, E., & Schulz, S. (2003). Impact pathway evaluation: An approach for achieving and attributing impact in complex systems. *Agricultural Systems*, *78*(2), 243–265. https://doi.org/10.1016/S0308-521X(03)00128-8

Drinkwater, L. E., & Snapp, S. S. (2007). Nutrients in Agroecosystems: Rethinking the Management Paradigm. In D. L. Sparks (Ed.), *Advances in Agronomy* (Vol. 92, pp. 163–186). Academic Press. https://doi.org/10.1016/S0065-2113(04)92003-2

Dungait, J. A. J., Hopkins, D. W., Gregory, A. S., & Whitmore, A. P. (2012). Soil organic matter turnover is governed by accessibility not recalcitrance. *Global Change Biology*, *18*(6), 1781–1796. https://doi.org/10.1111/j.1365-2486.2012.02665.x

Eastwood, C., Klerkx, L., & Nettle, R. (2017). Dynamics and distribution of public and private research and Extension roles for technological innovation and diffusion: Case studies of the implementation and adaptation of precision farming technologies. *Journal of Rural Studies*, *49*, 1–12. https://doi.org/10.1016/j.jrurstud.2016.11.008

Eckert, E. & Bell, A..(2005). Invisible force: Farmers' mental models and how they influence learning and actions. Retrieved November 1, 2023 from https://www.researchgate.net/publication/291702902_Invisible_force_Farmers'_mental_models_and_how_they_influence_learning_and_actions.

Eckert, E., & Bell, A. (2006). Continuity and Change: Themes of Mental Model Development Among Small-Scale Farmers. The Journal of Extension, 44(1), Article 4. https://tigerprints.clemson.edu/joe/vol44/iss1/4.

FAO. (2018). The10 elements of agroecology: Guiding the transition to sustainable food and agricultural systems. Retrieved November 1, 2023 from https://www.fao.org/3/i9037en/i9037en.pdf

Galford, G. L., Faulkner, J., Dupigny-Giroux, L.-A., Posner, S., & Edling, L. (2021). *Vermont Climate Assessment*. https://site.uvm.edu/vtclimateassessment/

Gliessman, S. (2022). Can agricultural Extension be of service to agroecology? *Agroecology and Sustainable Food Systems*, *46*(7), 953–954. https://doi.org/10.1080/21683565.2022.2095731

Glover, D., Sumberg, J., Ton, G., Andersson, J., & Badstue, L. (2019). Rethinking technological change in smallholder agriculture. *Outlook on Agriculture*, *48*(3), 169–180. https://doi.org/10.1177/0030727019864978

Goldberg, M. H., Gustafson, A., & van der Linden, S. (2020). Leveraging Social Science to Generate Lasting Engagement with Climate Change Solutions. *One Earth*, *3*(3), 314–324. https://doi.org/10.1016/j.oneear.2020.08.011

Halbrendt, J., Gray, S. A., Crow, S., Radovich, T., Kimura, A. H., & Tamang, B. B. (2014). Differences in farmer and expert beliefs and the perceived impacts of conservation agriculture. *Global Environmental Change*, *28*, 50–62. https://doi.org/10.1016/j.gloenvcha.2014.05.001

Hammond-Wagner, C. R., Gourevitch, J., Horner, K., Kinnebrew, E., Recchia, E., White, A., Wiegman, A., Ricketts, T., & Roy, E. (2019). Payment for Ecosystem Services for Vermont. *Gund Institute for Environment.*, *19–01*, 40.

Hermans, T. D. G., Whitfield, S., Dougill, A. J., & Thierfelder, C. (2021). Why we should rethink 'adoption' in agricultural innovation: Empirical insights from Malawi. *Land Degradation & Development*, *32*(4), 1809–1820. https://doi.org/10.1002/ldr.3833

Hoffman, M., Lubell, M., & Hillis, V. (2014). Linking knowledge and action through mental models of sustainable agriculture. *Proceedings of the National Academy of Sciences*, *111*(36), 13016–13021. https://doi.org/10.1073/pnas.1400435111

Holling, C. S. (1973). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, *4*(1), 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245

Horner, C. (2023). Exploring Potential Domains of Agroecological Transformation in the United States. *Graduate College Dissertations and Theses*. https://scholarworks.uvm.edu/graddis/1658

Jabbour, R., Zwickle, S., Gallandt, E. R., McPhee, K. E., Wilson, R. S., & Doohan, D. (2014). Mental models of organic weed management: Comparison of New England US farmer and expert models. *Renewable Agriculture and Food Systems*, *29*(4), 319–333. https://doi.org/10.1017/S1742170513000185

Karlen, D. L., Goeser, N. J., Veum, K. S., & Yost, M. A. (2017). On-farm soil health evaluations: Challenges and opportunities. *Journal of Soil and Water Conservation*, *72*(2), 26A-31A. https://doi.org/10.2489/jswc.72.2.26A

Kremen, C., & Miles, A. (2012). Ecosystem Services in Biologically Diversified versus Conventional Farming Systems: Benefits, Externalities, and Trade-Offs. *Ecology and Society*, *17*. https://doi.org/10.5751/ES-05035-170440

Kuehne, G., Llewellyn, R., Pannell, D. J., Wilkinson, R., Dolling, P., Ouzman, J., & Ewing, M. (2017). Predicting farmer uptake of new agricultural practices: A tool for research, Extension and policy. *Agricultural Systems*, *156*, 115–125. https://doi.org/10.1016/j.agsy.2017.06.007

Lee, R., & Ahtone, T. (2020, March 20). Land-grab Universities. *High Country News*.

Lehmann, J., Bossio, D. A., Kögel-Knabner, I., & Rillig, M. C. (2020). The concept and future prospects of soil health. *Nature Reviews Earth & Environment*, *1*(10), Article 10. https://doi.org/10.1038/s43017-020-0080-8

Magdoff, F., & Van Es, H. (1993). Building Soils for Better Crops: Organic Matter Management. *Soil Science*, *156*(5), 371. https://doi.org/10.1097/00010694-199311000-00014

Mason, R. E., Merrill, S. C., Görres, J., Faulkner, J., & Niles, M. T. (2021). Agronomic and environmental performance of dairy farms in a warmer, wetter climate. *Journal of Soil and Water Conservation*, *76*(1), 76–88. https://doi.org/10.2489/jswc.2021.00169

McAllister, J., & Bell, S. (2021). Sustainable Agriculture Through Sustainable Learning: An Educator's Guide to Best Practices for Adult Learning. Retrieved October 3, 2023 from https://www.sare.org/resources/sustainable-agriculture-through-sustainable-learning/.

Meuwissen, M. P. M., Feindt, P. H., Spiegel, A., Termeer, C. J. A. M., Mathijs, E., Mey, Y. de, Finger, R., Balmann, A., Wauters, E., Urquhart, J., Vigani, M., Zawalińska, K., Herrera, H., Nicholas-Davies, P., Hansson, H., Paas, W., Slijper, T., Coopmans, I., Vroege, W., … Reidsma, P. (2019). A framework to assess the resilience of farming systems. *Agricultural Systems*, *176*, 102656. https://doi.org/10.1016/j.agsy.2019.102656

Moebius-Clune, B. N., Moebius-Clune, D. J., Gugino, B. K., Idowu, O. J., Schindelbeck, R. R., Ristow, A. J., van Es, H. M., Thies, J. E., & Shayler, H. A. (2016). Comprehensive Assessment of Soil Health The Cornell Framework, Edition 3.2,. *Cornell University, Geneva, NY.*

Montes de Oca Munguia, O., Pannell, D. J., Llewellyn, R., & Stahlmann-Brown, P. (2021). Adoption pathway analysis: Representing the dynamics and diversity of adoption for agricultural practices. *Agricultural Systems*, *191*, 103173. https://doi.org/10.1016/j.agsy.2021.103173

Moon, K., Guerrero, A. M., Adams, Vanessa. M., Biggs, D., Blackman, D. A., Craven, L., Dickinson, H., & Ross, H. (2019). Mental models for conservation research and practice. *Conservation Letters*, *12*(3), e12642. https://doi.org/10.1111/conl.12642

Neher, D. A., Harris, J. M., Horner, C. E., Scarborough, M. J., Badireddy, A. R., Faulkner, J. W., White, A. C., Darby, H. M., Farley, J. C., & Bishop-von Wettberg, E. J. (2022). Resilient Soils for Resilient Farms: An Integrative Approach to Assess, Promote, and Value Soil Health for Small- and Medium-Size Farms. *Phytobiomes Journal*, *6*(3), 201–206. https://doi.org/10.1094/PBIOMES-10-21-0060-P

Norris, C. E., & Congreves, K. A. (2018). Alternative Management Practices Improve Soil Health Indices in Intensive Vegetable Cropping Systems: A Review.

Frontiers in Environmental Science, *6*. https://www.frontiersin.org/articles/10.3389/fenvs.2018.00050

NRCS. (2023, October 2). *Soil Health | Natural Resources Conservation Service*. https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soils/soil-health

Pan, D. (2014). The impact of agricultural Extension on farmer nutrient management behavior in chinese rice production: A household-level analysis. *Sustainability (Switzerland)*, *6*(10), 6644–6665. https://doi.org/10.3390/su6106644

Pannell, D. J., & Claassen, R. (2020). The Roles of Adoption and Behavior Change in Agricultural Policy. *Applied Economic Perspectives and Policy*, *42*(1), 31–41. https://doi.org/10.1002/aepp.13009

Prager, K., & Curfs, M. (2016). Using mental models to understand soil management. *Soil Use and Management*, *32*(1), 36–44. https://doi.org/10.1111/sum.12244

Prager, K., Schuler, J., Helming, K., Zander, P., Ratinger, T., & Hagedorn, K. (2011). Soil degradation, farming practices, institutions and policy responses: An analytical framework. *Land Degradation & Development*, *22*(1), 32–46. https://doi.org/10.1002/ldr.979

Prokopy, L. S., Floress, K., Arbuckle, J. G., Church, S. P., Eanes, F. R., Gao, Y., Gramig, B. M., Ranjan, P., & Singh, A. S. (2019). Adoption of agricultural conservation practices in the United States: Evidence from 35 years of quantitative literature. *Journal of Soil and Water Conservation*, *74*(5), 520–534. https://doi.org/10.2489/jswc.74.5.520

Required Agricultural Practices | Agency of Agriculture Food and Markets. (n.d.). Retrieved August 4, 2022, from https://agriculture.vermont.gov/rap

Rittel, H. W. J., & Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy Sciences*, *4*(2), 155–169. https://doi.org/10.1007/BF01405730

Roesch-McNally, G. E., Basche, A. D., Arbuckle, J. G., Tyndall, J. C., Miguez, F. E., Bowman, T., & Clay, R. (2018). The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. *Renewable Agriculture and Food Systems*, *33*(4), 322–333. https://doi.org/10.1017/S1742170517000096

Rogers, EM. (2003). Diffusion of innovations. 5. New York: Free Press; 2003. *Free Press*.

Rust, N. A., Stankovics, P., Jarvis, R. M., Morris-Trainor, Z., de Vries, J. R., Ingram, J., Mills, J., Glikman, J. A., Parkinson, J., Toth, Z., Hansda, R., McMorran, R., Glass, J., & Reed, M. S. (2022). Have farmers had enough of experts?

Environmental Management, *69*(1), 31–44. https://doi.org/10.1007/s00267-021-01546-y

Sattar, R. S., Wang, S., Muqadas, M., Ashraf, M. F., & Tahir, M. N. (2017). Qualitative and quantitative approaches to study adoption of sustainable agricultural practices: A research-note on mixed method approach. In *International Journal of Agricultural Extension and Rural Development* (Vol. 5, Issue 2).

Schattman, R. E., Hurley, S. E., Greenleaf, H. L., Niles, M. T., & Caswell, M. (2020). Visualizing Climate Change Adaptation: An Effective Tool for Agricultural Outreach? *Weather, Climate, and Society*, *12*(1), 47–61. https://doi.org/10.1175/WCAS-D-19-0049.1

Schattman, R. E., Méndez, V. E., Merrill, S. C., & Zia, A. (2018). Mixed methods approach to understanding farmer and agricultural advisor perceptions of climate change and adaptation in Vermont, United States. *Agroecology and Sustainable Food Systems*, *42*(2), 121–148. https://doi.org/10.1080/21683565.2017.1357667

Schipanski, M. E., Barbercheck, M., Douglas, M. R., Finney, D. M., Haider, K., Kaye, J. P., Kemanian, A. R., Mortensen, D. A., Ryan, M. R., Tooker, J., & White, C. (2014). A framework for evaluating ecosystem services provided by cover crops in agroecosystems. *Agricultural Systems*, *125*, 12–22. https://doi.org/10.1016/j.agsy.2013.11.004

Segura, C., Sun, G., McNulty, S., & Zhang, Y. (2014). Potential impacts of climate change on soil erosion vulnerability across the conterminous United States. *Journal of Soil and Water Conservation*, *69*(2), 171–181. https://doi.org/10.2489/jswc.69.2.171

Snapp, S. S., Swinton, S. M., Labarta, R., Mutch, D., Black, J. R., Leep, R., Nyiraneza, J., & O'Neil, K. (2005). Evaluating Cover Crops for Benefits, Costs and Performance within Cropping System Niches. *Agronomy Journal*, *97*(1), 322–332. https://doi.org/10.2134/agronj2005.0322a

Soil Health Cover Crops. (2023). Retrieved September 25, 2023, from https://www.kelloggs.com/en_US/articles/sustainability/soil-health-cover-crops.html

Springer-Heinze, A., Hartwich, F., Henderson, J. S., Horton, D., & Minde, I. (2003). Impact pathway analysis: An approach to strengthening the impact orientation of agricultural research. *Agricultural Systems*, *78*, 267–285. https://doi.org/10.1016/S0308-521X(03)00129-X

Stott, D. E., & Moebius-Clune, B. N. (2017a). Soil health: Challenges and opportunities. *Global Soil Security*, 109–121.

Stott, D. E., & Moebius-Clune, B. N. (2017b). Soil Health: Challenges and Opportunities. In D. J. Field, C. L. S. Morgan, & A. B. McBratney (Eds.), *Global Soil Security* (pp. 109–121). Springer International Publishing. https://doi.org/10.1007/978-3-319-43394-3_10

Suvedi, M., & Kaplowitz, M. (2016). What Every Extension Worker Should Know. Core Competency Handbook. U.S. Agency for International Development (USAID) project Modernizing Extension and Advisory Services (MEAS) www.meas-Extension.org.

Tallaksen, J. (2021). *What is Agricultural Resilience?* University of Minnesota Extension. https://wcroc.cfans.umn.edu/about-us/wcroc-news/ag-resilience

Tittonell, P. (2020). Assessing resilience and adaptability in agroecological transitions. *Agricultural Systems*, *184*, 102862. https://doi.org/10.1016/j.agsy.2020.102862

Tong, A., Sainsbury, P., & Craig, J. (2007). Consolidated criteria for reporting qualitative research (COREQ): A 32-item checklist for interviews and focus groups. *International Journal for Quality in Health Care*, *19*(6), 349–357. https://doi.org/10.1093/intqhc/mzm042

Utter, A., White, A., Méndez, V. E., & Morris, K. (2021). Co-creation of knowledge in agroecology. *Elementa: Science of the Anthropocene*, *9*(1), 00026. https://doi.org/10.1525/elementa.2021.00026

van den Broek, K. L., Luomba, J., van den Broek, J., & Fischer, H. (2021). Evaluating the Application of the Mental Model Mapping Tool (M-Tool). *Frontiers in Psychology*, *12*, 761882. https://doi.org/10.3389/fpsyg.2021.761882

van Hulst, F., Ellis, R., Prager, K., & Msika, J. (2020). Using co-constructed mental models to understand stakeholder perspectives on agro-ecology. *International Journal of Agricultural Sustainability*, *18*(2), 172–195. https://doi.org/10.1080/14735903.2020.1743553

Vollstedt, M., & Rezat, S. (2019). An Introduction to Grounded Theory with a Special Focus on Axial Coding and the Coding Paradigm. In G. Kaiser & N. Presmeg (Eds.), *Compendium for Early Career Researchers in Mathematics Education* (pp. 81–100). Springer International Publishing. https://doi.org/10.1007/978-3-030-15636-7_4

Wade, J., Culman, S. W., Gasch, C. K., Lazcano, C., Maltais-Landry, G., Margenot, A. J., Martin, T. K., Potter, T. S., Roper, W. R., Ruark, M. D., Sprunger, C. D., & Wallenstein, M. D. (2022). Rigorous, empirical, and quantitative: A proposed pipeline for soil health assessments. *Soil Biology and Biochemistry*, *170*, 108710. https://doi.org/10.1016/j.soilbio.2022.108710

Warner, K. D. (2008). Agroecology as Participatory Science: Emerging Alternatives to Technology Transfer Extension Practice. *Science, Technology, & Human Values*, *33*(6), 754–777. https://doi.org/10.1177/0162243907309851

Wezel, A., Herren, B. G., Kerr, R. B., Barrios, E., Gonçalves, A. L. R., & Sinclair, F. (2020). Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agronomy for Sustainable Development*, *40*(6), 40. https://doi.org/10.1007/s13593-020-00646-z

White, A., Faulkner, J., Conner, D., Méndez, V., & Niles, M. (2022). "How can you put a price on the environment?" Farmer perspectives on stewardship and payment for ecosystem services. *Journal of Soil and Water Conservation*, 00041. https://doi.org/10.2489/jswc.2022.00041

CHAPTER 5: CONCLUSION

Vermont vegetable farmers approach soil health practices with a depth of knowledge, innovation, and intuition that has fostered a healthy, resilient agroecosystem. Farmers demonstrate their ingenuity by adapting practices to changing markets and climatic uncertainty. Information transfer from farmer to farmer has broadened this web of knowledge, creating a unique and ecological set of agricultural practices in Vermont. My work with farmers throughout the course of these research projects has enhanced my admiration for the integrated way in which they care for the soil, the crops, their peers, the communities in which they farm, and the broader ecosystem.

This research revealed the immense challenges of "improving" soil health practices and outcomes on diversified vegetable farms. In many ways, this dissertation traces my own agroecological evolution, from asking biophysical and agronomic questions to exploring the social and political factors that influence farmers. In Chapter Two, I sought to answer seemingly simple questions about the timing and quantity of nitrogen availability after legume cover crop incorporation with the hopes of providing farmers with clear guidance regarding these practices. Yet the data collected from multiple farm sites across two years revealed confounding interactions between soil, plants, weather, and farmer management. This research demonstrated that there is currently no simple test to accurately measure available nitrogen across many soil scenarios, nor is there a simple metric for predicting availability. Instead, this project illustrated that soil health on many vegetable farms has been well-managed, and as a result, is dynamic and complex. Efforts to merely quantify soil nutrients ignore the importance soil ecology, farmer management, and environmental factors.

Exploring the implementation of high tunnel nutrient recommendations and the influence practices have on yield outcomes illustrates the next phase of my understanding of the relationships between context, practices, and outcomes. Every farm that contributed information to this project is different, which lent unique power to the data collected. Initially, the lack of controls in this project appeared to be a weakness, but in reality enabled a clear understanding of what practices truly influenced yield. This type of research can lead to key findings that are easy for farmers to implement while also informing future research. This project also made it clear that although high tunnels have incredible production potential, few growers have circumstances that enable optimization.

The final chapter of this dissertation addressed the important question of motivation behind the practices discussed in the previous two chapters. It is important to note that many of the farmers interviewed were also involved in one of the other two chapters and are well-representative of Vermont vegetable growers. Developing the mental models during the interviews fully illustrated the integrated and thoughtful approach many growers have when considering soil health. These interviews demonstrated that many growers already employed an agroecological approach to soil health practices but that barriers, or “lock-ins”, are a reality.

Taken together, these chapters illustrate key opportunities to better support Vermont vegetable farmers. First, growers will benefit from agronomic guidance that accounts for the complexity of their soil health practices. This assistance should be offered in conjunction with farmer knowledge and site-specific context. As Chapter Two makes clear, there are no “text-book” recommendations for farmers who already have good soil health. Second, participatory research provides an opportunity to identify low-cost and easy to implement practices that improve outcomes. Finally, farmers and their soil health exist within the context of a very complicated world with many conflicting forces. Farmers, their soil health, and their livelihoods can only be supported with an understanding of these underlying factors. This work provides exciting insight into new approaches to support farmers and the agroecosystem we all depend upon.

COMPREHENSIVE BIBLIOGRAPHY

Aare, A. K., Lund, S., & Hauggaard-Nielsen, H. (2021). Exploring transitions towards sustainable farming practices through participatory research – The case of Danish farmers' use of species mixtures. Agricultural Systems, 189, 103053. https://doi.org/10.1016/j.agsy.2021.103053

Allan, C., Cooke, P., Higgins, V., Leith, P., Bryant, M., & Cockfield, G. (2022). Adoption; a relevant concept for agricultural land management in the 21 century? Outlook on Agriculture, 51(4), 375–383. https://doi.org/10.1177/00307270221126540

Allan, C., Cooke, P., Higgins, V., Leith, P., Bryant, M., & Cockfield, G. (2022). Adoption; a relevant concept for agricultural land management in the 21 century? Outlook on Agriculture, 51(4), 375–383. https://doi.org/10.1177/00307270221126540

Anderson, C. R., Bruil, J., Chappell, M. J., Kiss, C., & Pimbert, M. P. (2019). From Transition to Domains of Transformation: Getting to Sustainable and Just Food Systems through Agroecology. Sustainability, 11(19), Article 19. https://doi.org/10.3390/su11195272

Artz, G., & Naeve, L. (2016). The Benefits and Challenges of Machinery Sharing Among Small-scale Fruit and Vegetable Growers. Journal of Agriculture, Food Systems, and Community Development, 6(3), Article 3. https://doi.org/10.5304/jafscd.2016.063.003

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

Bardenhagen, C. J., Howard, P. H., & Gray, S. A. (2020). Farmer Mental Models of Biological Pest Control: Associations With Adoption of Conservation Practices in Blueberry and Cherry Orchards. Frontiers in Sustainable Food Systems, 4, 54. https://doi.org/10.3389/fsufs.2020.00054

Baumgart-Getz, A., Prokopy, L. S., & Floress, K. (2012). Why farmers adopt best management practice in the United States: A meta-analysis of the adoption literature. Journal of Environmental Management, 96(1), 17–25. https://doi.org/10.1016/j.jenvman.2011.10.006

Baumgartner, J. A. (2013). Biodiversity Continuum Chart. Wild Farm Alliance. https://www.wildfarmalliance.org/biodiversity_continuum_chart. Retrieved 10/20/23.

Biardeau, L., Crebbin-Coates, R., Keerati, R., Litke, S., & Rodríguez, H. (2016). Soil Health and Carbon Sequestration in US Croplands: A Policy Analysis Prepared for: Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture (USDA) and the Berkeley Food Institute (BFI).

Birkhaeuser, D., Evenson, R. E., & Feder, G. (1991). The Economic Impact of Agricultural Extension: A Review. In Source: Economic Development and Cultural Change (Vol. 39, Issue 3).

Blevins, R. L., Herbek, J. H., & Frye, W. W. (1990). Legume Cover Crops as a Nitrogen Source for No-Till Corn and Grain Sorghum. Agronomy Journal, 82(4), 769–772. https://doi.org/10.2134/agronj1990.00021962008200040023x

Both, A. J., Reiss, E., Sudal, J. F., Holmstrom, K. E., Wyenandt, C. A., Kline, W. L., & Garrison, S. A. (2007). Evaluation of a Manual Energy Curtain for Tomato Production in High Tunnels. HortTechnology, 17(4), 467–472. https://doi.org/10.21273/HORTTECH.17.4.467

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. Qualitative Research in Psychology, 3(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Bruce, A. B., Maynard, E. T., Valliant, J. C. D., & Farmer, J. R. (2021). Farm Type and High Tunnel Management: Connections between Farm Characteristics and High Tunnel Outcomes in Indiana. HortTechnology, 31(5), 566–576. https://doi.org/10.21273/HORTTECH04783-21

Campbell-Nelson, K. Grubinger, V.,Hoskins, B., Radin, A, Sideman, R., “2018 New England High Tunnel Survey.” ag.mass.edu, 2019. Retrieved from https://ag.umass.edu/sites/ag.umass.edu/files/reports/2018_high_tunnel_survey_report.pdf on 10/24/2023.

Carey, E. E., Jett, L., Lamont, W. J., Nennich, T. T., Orzolek, M. D., & Williams, K. A. (2009). Horticultural Crop Production in High Tunnels in the United States: A Snapshot. HortTechnology, 19(1), 37–43. https://doi.org/10.21273/HORTSCI.19.1.37

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

Carlisle, L., Esquivel, K., Baur, P., Ichikawa, N. F., Olimpi, E. M., Ory, J., Waterhouse, H., Iles, A., Karp, D. S., Kremen, C., & Bowles, T. M. (2022). Organic farmers face persistent barriers to adopting diversification practices in California’s Central Coast. Agroecology and Sustainable Food Systems, 46(8), 1145–1172. https://doi.org/10.1080/21683565.2022.2104420

Caswell, M., Maden, R., McCune, N., Mendez, V., Bucini, G., Anderzen, J., Izzo, V., Hurley, S. E., Gould, R. K., Faulkner, J. W., & Juncos-Gautier, M. (2021). Amplifying Agroecology in Vermont: Principles and Processes to Foster Food Systems Sustainability. USDA Agricultural Research Service (ARS) Center. https://scholarworks.uvm.edu/arsfoodsystems/4

Clark, J. D., Fernández, F. G., Veum, K. S., Camberato, J. J., Carter, P. R., Ferguson, R. B., Franzen, D. W., Kaiser, D. E., Kitchen, N. R., Laboski, C. A. M., Nafziger, E. D., Rosen, C. J., Sawyer, J. E., & Shanahan, J. F. (2020). Adjusting corn nitrogen management by including a mineralizable-nitrogen test with the preplant and presidedress nitrate tests. Agronomy Journal, 112(4), 3050–3064. https://doi.org/10.1002/agj2.20228

Coleman, E. (2018). The New Organic Grower. Chelsea Green Publishing Pub.

Collins, C. S., & Stockton, C. M. (2018). The Central Role of Theory in Qualitative Research. International Journal of Qualitative Methods, 17(1), 1609406918797475. https://doi.org/10.1177/1609406918797475

Conner, D. S., Waldman, K. B., Montri, A. D., Hamm, M. W., & Biernbaum, J. A. (2010). Hoophouse Contributions to Economic Viability: Nine Michigan Case Studies. HortTechnology, 20(5), 877–884. https://doi.org/10.21273/HORTTECH.20.5.877

Conner, D., DeWitt, R.-L., Inwood, S., & Archer, M. (2015). Social Responsibility and Community Development in Vermont's Food Business. Journal of Food Research, 4, 93. https://doi.org/10.5539/jfr.v4n6p93

Creswell, J. W., & Miller, D. L. (2000). Determining Validity in Qualitative Inquiry. Theory Into Practice, 39(3), 124–130. https://doi.org/10.1207/s15430421tip3903_2

Darby, H., Burke, C., Cummings, E., Harwood, H., Madden, R., & Monahan, S. (2012). Cover Crop Planting Date x Seeding Rate Trial. Northwest Crops & Soils Program. https://scholarworks.uvm.edu/nwcsp/37

DeVincentis, A. J., Solis, S. S., Bruno, E. M., Leavitt, A., Gomes, A., Rice, S., & Zaccaria, D. (2020). Using cost-benefit analysis to understand adoption of winter cover cropping in California's specialty crop systems. Journal of Environmental Management, 261, 110205. https://doi.org/10.1016/j.jenvman.2020.110205

Dlott, J. W., Altieri, M. A., & Masumoto, M. (1994). Exploring the theory and practice of participatory research in US sustainable agriculture: A case study in insect pest management. Agriculture and Human Values, 11(2), 126–139. https://doi.org/10.1007/BF01530453

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

Douthwaite, B., Kuby, T., van de Fliert, E., & Schulz, S. (2003). Impact pathway evaluation: An approach for achieving and attributing impact in complex systems. Agricultural Systems, 78(2), 243–265. https://doi.org/10.1016/S0308-521X(03)00128-8

Drenovsky, R. E., Vo, D., Graham, K. J., & Scow, K. M. (2004). Soil Water Content and Organic Carbon Availability Are Major Determinants of Soil Microbial Community Composition. Microbial Ecology, 48(3), 424–430. https://doi.org/10.1007/s00248-003-1063-2

Drinkwater, L. E., & Snapp, S. S. (2007). Nutrients in Agroecosystems: Rethinking the Management Paradigm. In D. L. Sparks (Ed.), Advances in Agronomy (Vol. 92, pp. 163–186). Academic Press. https://doi.org/10.1016/S0065-2113(04)92003-2

Dungait, J. A. J., Hopkins, D. W., Gregory, A. S., & Whitmore, A. P. (2012). Soil organic matter turnover is governed by accessibility not recalcitrance. Global Change Biology, 18(6), 1781–1796. https://doi.org/10.1111/j.1365-2486.2012.02665.x

Eastwood, C., Klerkx, L., & Nettle, R. (2017). Dynamics and distribution of public and private research and Extension roles for technological innovation and diffusion: Case studies of the implementation and adaptation of precision farming technologies. Journal of Rural Studies, 49, 1–12. https://doi.org/10.1016/j.jrurstud.2016.11.008

Eaton, Connor, Year-round management of high tunnel production systems: spinach and tomato (2016). Master's Theses and Capstones. 1088. https://scholars.unh.edu/thesis/1088.

Eckert, E. & Bell, A..(2005). Invisible force: Farmers' mental models and how they influence learning and actions. Retrieved November 1, 2023 from https://www.researchgate.net/publication/291702902_Invisible_force_Farmers'_mental_models_and_how_they_influence_learning_and_actions.

Eckert, E., & Bell, A. (2006). Continuity and Change: Themes of Mental Model Development Among Small-Scale Farmers. The Journal of Extension, 44(1), Article 4. https://tigerprints.clemson.edu/joe/vol44/iss1/4.

Evanylo, G., Sherony, C., Spargo, J., Starner, D., Brosius, M., & Haering, K. (2008). Soil and water environmental effects of fertilizer-, manure-, and compost-based fertility practices in an organic vegetable cropping system. Agriculture, Ecosystems & Environment, 127(1), 50–58. https://doi.org/10.1016/j.agee.2008.02.014

FAO. (2018). The10 elements of agroecology: guiding the transition to sustainable food and agricultural systems. Food and Agriculture Organization of the United Nations (FAO). Retrieved November 1, 2023 from https://www.fao.org/3/i9037en/i9037en.pdf

Ferguson, B. J., Mens, C., Hastwell, A. H., Zhang, M., Su, H., Jones, C. H., Chu, X., & Gresshoff, P. M. (2019). Legume nodulation: The host controls the party. Plant, Cell & Environment, 42(1), 41–51. https://doi.org/10.1111/pce.13348

Finney, D. M., White, C. M., & Kaye, J. P. (2016). Biomass Production and Carbon/Nitrogen Ratio Influence Ecosystem Services from Cover Crop Mixtures. Agronomy Journal, 108(1), 39–52. https://doi.org/10.2134/agronj15.0182

Foust-Meyer, N., & O'Rourke, M. (2015). High Tunnels for Local Food Systems: Subsidies, Equity, and Profitability. Journal of Agriculture, Food Systems, and Community Development, 1–12. https://doi.org/10.5304/jafscd.2015.052.015

Galford, G. L., Faulkner, J., Dupigny-Giroux, L.-A., Posner, S., & Edling, L. (2021). Vermont Climate Assessment. https://site.uvm.edu/vtclimateassessment/

Galinato, S. P., & Miles, C. A. (2013). Economic Profitability of Growing Lettuce and Tomato in Western Washington under High Tunnel and Open-field Production Systems. HortTechnology, 23(4), 453–461. https://doi.org/10.21273/HORTTECH.23.4.453

Gaskell, M., & Smith, R. (2007). Nitrogen Sources for Organic Vegetable Crops. HortTechnology Hortte, 17(4), 431–441. https://doi.org/10.21273/HORTTECH.17.4.431

Gaskin, J., Cabrera, M., & Kissel, D. (2016). Predicting Nitrogen Release from Cover Crops: THE COVER CROP NITROGEN AVAILABILITY CALCULATOR. University of Georgia Extension. https://Extension.uga.edu/publications/detail.html?number=B1466

Gaskin, J., Hancock, D., Uttam, S., & Chatam, K. (2022). Cover Crop Biomass Sampling. University of Georgia. Retrieved on August 3, 2023 from https://extension.uga.edu/publications/detail.html?number=C1077&title=cover-crop-biomass-sampling.

General Mills. (2023). " A healthier planet – Regenerative agriculture." Retrieved September 25, 2023, from https://www.generalmills.com/how-we-make-it/healthier-planet/environmental-impact/regenerative-agriculture

Gent, M. P. N. (1992). Yield response to planting date, ventilation and soil temperature on growth and nutrition of tomato high tunnels. Plant Soil, 145, 81–91.

Gershuny, G., & Smillie, J. (1999, March 3). The Soul of Soil—Chelsea Green Publishing. https://www.chelseagreen.com/product/the-soul-of-soil/

Gliessman, S. (2022). Can agricultural Extension be of service to agroecology? Agroecology and Sustainable Food Systems, 46(7), 953–954. https://doi.org/10.1080/21683565.2022.2095731

Glover, D., Sumberg, J., Ton, G., Andersson, J., & Badstue, L. (2019). Rethinking technological change in smallholder agriculture. Outlook on Agriculture, 48(3), 169–180. https://doi.org/10.1177/0030727019864978

Goldberg, M. H., Gustafson, A., & van der Linden, S. (2020). Leveraging Social Science to Generate Lasting Engagement with Climate Change Solutions. One Earth, 3(3), 314–324. https://doi.org/10.1016/j.oneear.2020.08.011

Goldy, R. (2012, December 14). Experience with growing tomatoes in high tunnels: Fertilization, quality and yield. MSU Extension. https://www.canr.msu.edu/news/experience_with_growing_tomatoes_in_high_tunnels_fertilization_quality_and

Grandy, A. S., Daly, A. B., Bowles, T. M., Gaudin, A. C. M., Jilling, A., Leptin, A., McDaniel, M. D., Wade, J., & Waterhouse, H. (2022). The nitrogen gap in soil health concepts and fertility measurements. Soil Biology and Biochemistry, 175, 108856. https://doi.org/10.1016/j.soilbio.2022.108856

Griffin, G., Jokela, W., Ross, D., Pettinelli, D., Morris, T., & Wolf, A. (2011). Recommended Soil Nitrate Tests. 493.

Grubinger, V. (2012). Organic Greenhouse Tomato Nutrition. University of Vermont Extension. Retrieved October 1, 2023 from http://www.uvm.edu/vtvegandberry/factsheets

Grubinger, V. P. (2011). Impact of Tropical Storm Irene on Vermont Agriculture. Retrieved October 1, 2023 from http://www.uvm.edu/vtvegandberry/factsheets

Halbrendt, J., Gray, S. A., Crow, S., Radovich, T., Kimura, A. H., & Tamang, B. B. (2014). Differences in farmer and expert beliefs and the perceived impacts of conservation agriculture. Global Environmental Change, 28, 50–62. https://doi.org/10.1016/j.gloenvcha.2014.05.001

Hammond Wagner, C., Gourevitch, J., Horner, K., Kinnebrew, E., Maden, B., Recchia, E., White, A., Wiegman, A., Ricketts, T., Roy Citation Hammond Wagner, E., Livingston, G., Markowitz, D., Audet, M., Ross, C., Kamman, N., Rupe, M., Magnan, M., Faulkner, J., Albee, R., … Koliba, C. (2019). Issue Paper Payment for Ecosystem Services for Vermont.

Hartz, T.K. & Miyao, G. & Mullen, R.J. & Cahn, Michael & Valencia, Jair & Brittan, K.L.. (1999). Potassium Requirements for Maximum Yield and Fruit Quality of Processing Tomato. Journal of the American Society for Horticultural Science. American Society for Horticultural Science. 124. 10.21273/JASHS.124.2.199.

Hartz, T. K. (2006). Vegetable Production Best Management Practices to Minimize Nutrient Loss. HortTechnology, 16(3), 398–403. https://doi.org/10.21273/HORTTECH.16.3.0398

Hartz, T. K., Bendixen, W. E., & Wierdsma, L. (2000). The Value of Presidedress Soil Nitrate Testing as a Nitrogen Management Tool in Irrigated Vegetable Production. HortScience, 35(4), 651–656. https://doi.org/10.21273/HORTSCI.35.4.651

Heckman, J. R. (2002). In-season Soil Nitrate Testing as a Guide to Nitrogen Management for Annual Crops. HortTechnology, 12(4), 706–710. https://doi.org/10.21273/HORTTECH.12.4.706

Heckman, J. R., Samulis, R., & Nitzsche, P. (2002). Sweet Corn Crop Nitrogen Status Evaluation by Stalk Testing. HortScience, 37(5), 783–786. https://doi.org/10.21273/HORTSCI.37.5.783

Heckman, J., Hlubik, W., Prostak, D. J., & Paterson, J. W. (1995). Pre-sidedress Soil Nitrate Test for Sweet Corn. HortScience: A Publication of the American Society for Horticultural Science, 30. https://doi.org/10.21273/HORTSCI.30.5.1033

Helling, A. P., Conner, D. S., Heiss, S. N., & Berlin, L. S. (2015). Economic Analysis of Climate Change Best Management Practices in Vermont Agriculture. Agriculture, 5(3), Article 3. https://doi.org/10.3390/agriculture5030879

Hendrickson, J. (2005). Grower to grower: Creating a livelihood on a fresh market vegetable farm. http://www.cias.wisc.edu/wp-content/uploads/2008/07/grwr2grwr.pdf

Hermans, T. D. G., Whitfield, S., Dougill, A. J., & Thierfelder, C. (2021). Why we should rethink ‘adoption’ in agricultural innovation: Empirical insights from Malawi. Land Degradation & Development, 32(4), 1809–1820. https://doi.org/10.1002/ldr.3833

Hodge, T., Healy, K., Emerson, B., & Dawson, J. (2019). Comparing Tomato varieties under organic high tunnel and open field management in the North Central region. eOrganic.

Hoffman, M., Lubell, M., & Hillis, V. (2014). Linking knowledge and action through mental models of sustainable agriculture. Proceedings of the National Academy of Sciences, 111(36), 13016–13021. https://doi.org/10.1073/pnas.1400435111

Holling, C. S. (1973). Resilience and Stability of Ecological Systems. Annual Review of Ecology and Systematics, 4(1), 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245

Horner, C. (2023). Exploring Potential Domains of Agroecological Transformation in the United States. Graduate College Dissertations and Theses. https://scholarworks.uvm.edu/graddis/1658

Hoskins, B., Sideman, R., & Hutton, M. (2016, April 12). Preliminary Soil Test Calibration for High Tunnel Production—Maine Food and Agriculture Center—University of Maine. Maine Food and Agriculture Center. https://umaine.edu/mainefoodandagcenter/2016/04/12/966/

Huang, K.-M., Guan, Z., & Hammami, A. (2022). The U.S. Fresh Fruit and Vegetable Industry: An Overview of Production and Trade. Agriculture, 12(10), Article 10. https://doi.org/10.3390/agriculture12101719

Hunter, B., Drost, D., Black, B., & Ward, R. (2012). Improving Growth and Productivity of Early-season High-tunnel Tomatoes with Targeted Temperature Additions. HortScience, 47(6), 733–740. https://doi.org/10.21273/HORTSCI.47.6.733

Ingwell, L. L., & Kaplan, I. (2019). Insect Exclusion Screens Reduce Cucumber Beetle Infestations in High Tunnels, Increasing Cucurbit Yield. Journal of Economic Entomology, 112(4), 1765–1773. https://doi.org/10.1093/jee/toz060

International Panel of Experts on Sustainable Food Systems. (2016). IPES-Food. (2016). From uniformity to diversity: A paradigm shift from industrial agriculture to diversified agroecological systems. (IPES). http://www.ipes-food.org

Ivy, A. (2014). BMPs Proper pruning and training.pdf. Retrieved September 28, 2023 from http://www.hort.cornell.edu/expo/proceedings/2015/high-tunnels/BMPs%20Proper%20pruning%20and%20training.pdf

Jabbour, R., Zwickle, S., Gallandt, E. R., McPhee, K. E., Wilson, R. S., & Doohan, D. (2014). Mental models of organic weed management: Comparison of New England US farmer and expert models. Renewable Agriculture and Food Systems, 29(4), 319–333. https://doi.org/10.1017/S1742170513000185

Jahanzad, E., Barker, A. V., Hashemi, M., Eaton, T., Sadeghpour, A., & Weis, S. A. (2016). Nitrogen Release Dynamics and Decomposition of Buried and Surface Cover Crop Residues. Agronomy Journal, 108(4), 1735–1741. https://doi.org/10.2134/agronj2016.01.0001

Janke, R. R., Altamimi, M. E., & Khan, M. (2017). The Use of High Tunnels to Produce Fruit and Vegetable Crops in North America. Agricultural Sciences, 8(7), Article 7. https://doi.org/10.4236/as.2017.87052

Jett, L. (2004). High Tunnel Tomato production. University of Missouri Extension.

Jett, L. W. (2006). Watering and Fertilizing Tomatoes in a High Tunnel. University of Missouri Extension.

Jilling, A., Keiluweit, M., Contosta, A. R., Frey, S., Schimel, J., Schnecker, J., Smith, R. G., Tiemann, L., & Grandy, A. S. (2018). Minerals in the rhizosphere: Overlooked mediators of soil nitrogen availability to plants and microbes. Biogeochemistry, 139(2), 103–122. https://doi.org/10.1007/s10533-018-0459-5

Karlen, D. L., Goeser, N. J., Veum, K. S., & Yost, M. A. (2017). On-farm soil health evaluations: Challenges and opportunities. Journal of Soil and Water Conservation, 72(2), 26A-31A. https://doi.org/10.2489/jswc.72.2.26A

Kaye, J. P., & Quemada, M. (2017). Using cover crops to mitigate and adapt to climate change. A review. Agronomy for Sustainable Development, 37(1), 4. https://doi.org/10.1007/s13593-016-0410-x

Knewtson, S. J. B., Carey, E. E., & Kirkham, M. B. (2010). Management Practices of Growers Using High Tunnels in the Central Great Plains of the United States. HortTechnology, 20(3), 639–645. https://doi.org/10.21273/HORTTECH.20.3.639

Knewtson, S. J. B., Janke, R., Kirkham, M. B., Williams, K. A., & Carey, E. E. (2010). Trends in Soil Quality Under High Tunnels. HortScience, 45(10), 1534–1538. https://doi.org/10.21273/HORTSCI.45.10.1534

Knewtson, S. J. B., Kirkham, M. B., Janke, R. R., Murray, L. W., & Carey, E. E. (2012). Soil Quality After Eight Years Under High Tunnels. HortScience, 47(11), 1630–1633. https://doi.org/10.21273/HORTSCI.47.11.1630

Kremen, C., & Miles, A. (2012). Ecosystem Services in Biologically Diversified versus Conventional Farming Systems: Benefits, Externalities, and Trade-Offs. Ecology and Society, 17. https://doi.org/10.5751/ES-05035-170440

Kuehne, G., Llewellyn, R., Pannell, D. J., Wilkinson, R., Dolling, P., Ouzman, J., & Ewing, M. (2017). Predicting farmer uptake of new agricultural practices: A tool for research, Extension and policy. Agricultural Systems, 156, 115–125. https://doi.org/10.1016/j.agsy.2017.06.007

Kuehne, G., Llewellyn, R., Pannell, D. J., Wilkinson, R., Dolling, P., Ouzman, J., & Ewing, M. (2017). Predicting farmer uptake of new agricultural practices: A tool for research, Extension and policy. Agricultural Systems, 156, 115–125. https://doi.org/10.1016/j.agsy.2017.06.007

Laboksi, C. A. M., & Peters, J. B. (2012). Nutrient Application Guidelines for Field, Vegetable, and Fruit Crops in Wisconsin (A2809).

Lake Champlain Basin Program. "Phosphorus Sources." Retrieved November 13, 2022, from https://www.lcbp.org/our-goals/clean-water/nutrients-and-cyanobacteria/phosphorus-sources/

Lawson, A., Fortuna, A. M., Cogger, C., Bary, A., & Stubbs, T. (2013). Nitrogen contribution of rye–hairy vetch cover crop mixtures to organically grown sweet corn. Renewable Agriculture and Food Systems, 28(1), 59–69. https://doi.org/10.1017/S1742170512000014

Lee, R., & Ahtone, T. (2020, March 20). Land-grab Universities. High Country News.

Lehmann, J., Bossio, D. A., Kögel-Knabner, I., & Rillig, M. C. (2020). The concept and future prospects of soil health. Nature Reviews Earth & Environment, 1(10), Article 10. https://doi.org/10.1038/s43017-020-0080-8

Lei, L., & McDonald, L. M. (2019). Soil Moisture and Temperature Effects on Nitrogen Mineralization in a High Tunnel Farming System. Communications in Soil Science and Plant Analysis, 50(17), 2140–2150. https://doi.org/10.1080/00103624.2019.1654503

Liebman, A. M., Grossman, J., Brown, M., Wells, M. S., Reberg-Horton, S. C., & Shi, W. (2018). Legume Cover Crops and Tillage Impact Nitrogen Dynamics in Organic Corn Production. Agronomy Journal, 110(3), 1046–1057. https://doi.org/10.2134/agronj2017.08.0474

Magdoff, F. (1991). Understanding the Magdoff Pre-Sidedress Nitrate Test for Corn. Journal of Production Agriculture, 4(3), 297–305. https://doi.org/10.2134/jpa1991.0297

Magdoff, F., & Van Es, H. (1993). Building Soils for Better Crops: Organic Matter Management. Soil Science, 156(5), 371. https://doi.org/10.1097/00010694-199311000-00014

Mapfumo, P., Adjei-Nsiah, S., Mtambanengwe, F., Chikowo, R., & Giller, K. E. (2013). Participatory action research (PAR) as an entry point for supporting climate change adaptation by smallholder farmers in Africa. Environmental Development, 5, 6–22. https://doi.org/10.1016/j.envdev.2012.11.001

Marshall, K., Erich, S., Hutton, M., Hutchinson, M., & Mallory, E. (2016). Nitrogen Availability from Compost in High Tunnel Tomato Production. Compost

Science & Utilization, 24(3), 147–158. https://doi.org/10.1080/1065657X.2015.1102663

Mason, R. E., Merrill, S. C., Görres, J., Faulkner, J., & Niles, M. T. (2021). Agronomic and environmental performance of dairy farms in a warmer, wetter climate. Journal of Soil and Water Conservation, 76(1), 76–88. https://doi.org/10.2489/jswc.2021.00169

Matts, C., Conner, D. S., Fisher, C., Tyler, S., & Hamm, M. W. (2016). Farmer perspectives of Farm to Institution in Michigan: 2012 survey results of vegetable farmers. Renewable Agriculture and Food Systems, 31(1), 60–71. https://doi.org/10.1017/S1742170514000465

Maynard, E. (2019). Managing the Environment in High Tunnels for Cool Season Vegetable Production. Retrieved November 1, 2023 from https://www.extension.purdue.edu/extmedia/ho/ho-297-w.pdf

McAllister, J., & Bell, S. (2021). Sustainable Agriculture Through Sustainable Learning: An Educator's Guide to Best Practices for Adult Learning. Retrieved October 3, 2023 from https://www.sare.org/resources/sustainable-agriculture-through-sustainable-learning/.

McIntosh, J. L. (1969). Bray and Morgan Soil Extractants Modified for Testing Acid Soils from Different Parent Materials1. Agronomy Journal, 61(2), 259–265. https://doi.org/10.2134/agronj1969.00021962006100020025x

Mefferd, A. (2017). The Greenhouse and Hoophouse Grower's Handbook—Chelsea Green Publishing. https://www.chelseagreen.com/product/the-greenhouse-and-hoophouse-growers-handbook/

Méndez, V. E., Caswell, M., Gliessman, S. R., & Cohen, R. (2017). Integrating Agroecology and Participatory Action Research (PAR): Lessons from Central America. Sustainability, 9(5), Article 5. https://doi.org/10.3390/su9050705

Meuwissen, M. P. M., Feindt, P. H., Spiegel, A., Termeer, C. J. A. M., Mathijs, E., Mey, Y. de, Finger, R., Balmann, A., Wauters, E., Urquhart, J., Vigani, M., Zawalińska, K., Herrera, H., Nicholas-Davies, P., Hansson, H., Paas, W., Slijper, T., Coopmans, I., Vroege, W., … Reidsma, P. (2019). A framework to assess the resilience of farming systems. Agricultural Systems, 176, 102656. https://doi.org/10.1016/j.agsy.2019.102656

Moebius-Clune, B. N., Moebius-Clune, D. J., Gugino, B. K., Idowu, O. J., Schindelbeck, R. R., Ristow, A. J., van Es, H. M., Thies, J. E., & Shayler, H. A. (2016). Comprehensive Assessment of Soil Health The Cornell Framework, Edition 3.2,. Cornell University, Geneva, NY.

Montes de Oca Munguia, O., Pannell, D. J., Llewellyn, R., & Stahlmann-Brown, P. (2021). Adoption pathway analysis: Representing the dynamics and diversity of adoption for agricultural practices. Agricultural Systems, 191, 103173. https://doi.org/10.1016/j.agsy.2021.103173

Montri, A., & Biernbaum, J. A. (2009). Management of the Soil Environment in High Tunnels. HortTechnology Hortte, 19(1), 34–36. https://doi.org/10.21273/HORTSCI.19.1.34

Moon, K., Guerrero, A. M., Adams, Vanessa. M., Biggs, D., Blackman, D. A., Craven, L., Dickinson, H., & Ross, H. (2019). Mental models for conservation research and practice. Conservation Letters, 12(3), e12642. https://doi.org/10.1111/conl.12642

Morris, T. (1998). Soil sample bag effects on pre-sidedress soil nitrate test concentrations. Communications in Soil Science and Plant Analysis - COMMUN SOIL SCI PLANT ANAL, 29, 2529–2537. https://doi.org/10.1080/00103629809370130

NASS Vermont full report. (2017). Retrieved August 29, 2023, from https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_State_Level/Vermont/

Neher, D. A., Harris, J. M., Horner, C. E., Scarborough, M. J., Badireddy, A. R., Faulkner, J. W., White, A. C., Darby, H. M., Farley, J. C., & Bishop-von Wettberg, E. J. (2022). Resilient Soils for Resilient Farms: An Integrative Approach to Assess, Promote, and Value Soil Health for Small- and Medium-Size Farms. Phytobiomes Journal, 6(3), 201–206. https://doi.org/10.1094/PBIOMES-10-21-0060-P

Nian, Y., Zhao, R., Tian, S., Zhao, X., & Gao, Z. (2022). Economic Analysis of Grafted Organic Tomato Production in High Tunnels. HortTechnology, 32(5), 459–470. https://doi.org/10.21273/HORTTECH05101-22

Nieder, R., Benbi, D. K., & Scherer, H. W. (2011). Fixation and defixation of ammonium in soils: A review. Biology and Fertility of Soils, 47(1), 1–14. https://doi.org/10.1007/s00374-010-0506-4

NOFA-VT. (2019). Cost of Production Factsheet. Retrieved September 19, 2023, from https://www.nofavt.org/resource-library/vegetable-cost-production

Norris, C. E., & Congreves, K. A. (2018). Alternative Management Practices Improve Soil Health Indices in Intensive Vegetable Cropping Systems: A Review. Frontiers in Environmental Science, 6. https://www.frontiersin.org/articles/10.3389/fenvs.2018.00050

NRCS. (2023, October 2). Soil Health | Natural Resources Conservation Service. https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soils/soil-health

Pan, D. (2014). The impact of agricultural Extension on farmer nutrient management behavior in chinese rice production: A household-level analysis. Sustainability (Switzerland), 6(10), 6644–6665. https://doi.org/10.3390/su6106644

Pannell, D. J., & Claassen, R. (2020). The Roles of Adoption and Behavior Change in Agricultural Policy. Applied Economic Perspectives and Policy, 42(1), 31–41. https://doi.org/10.1002/aepp.13009

Papadopoulos, A. (1991). Growing greenhouse tomatoes in soil and in soilless media. University of Wisconsin - Madison.

Parr, M., Grossman, J. M., Reberg-Horton, S. C., Brinton, C., & Crozier, C. (2011). Nitrogen Delivery from Legume Cover Crops in No-Till Organic Corn Production. Agronomy Journal, 103(6), 1578–1590. https://doi.org/10.2134/agronj2011.0007

Perkus, E. A., Grossman, J. M., Pfeiffer, A., Rogers, M. A., & Rosen, C. J. (2022). Exploring Overwintered Cover Crops as a Soil Management Tool in Upper-midwest High Tunnels. *HortScience*, *57*(2), 171-180. Retrieved Dec 1, 2023, from https://doi.org/10.21273/HORTSCI15987-21

Perrone, S., Grossman, J., Liebman, A., Sooksa-nguan, T., & Gutknecht, J. (2020). Nitrogen fixation and productivity of winter annual legume cover crops in Upper Midwest organic cropping systems. Nutrient Cycling in Agroecosystems, 117(1), 61–76. https://doi.org/10.1007/s10705-020-10055-z

Poffenbarger, H. J., Mirsky, S. B., Weil, R. R., Kramer, M., Spargo, J. T., & Cavigelli, M. A. (2015). Legume Proportion, Poultry Litter, and Tillage Effects on Cover Crop Decomposition. Agronomy Journal, 107(6), 2083–2096. https://doi.org/10.2134/agronj15.0065

Prager, K., & Curfs, M. (2016). Using mental models to understand soil management. Soil Use and Management, 32(1), 36–44. https://doi.org/10.1111/sum.12244

Prager, K., Schuler, J., Helming, K., Zander, P., Ratinger, T., & Hagedorn, K. (2011). Soil degradation, farming practices, institutions and policy responses: An analytical framework. Land Degradation & Development, 22(1), 32–46. https://doi.org/10.1002/ldr.979

Prasad, R., & Chakraborty, D. (2019). Phosphorus Basics: Understanding Phosphorus Forms and Their Cycling in the Soil. Alabama Cooperative Extension System.

https://www.aces.edu/blog/topics/crop-production/understanding-phosphorus-forms-and-their-cycling-in-the-soil/

Prokopy, L. S., Floress, K., Arbuckle, J. G., Church, S. P., Eanes, F. R., Gao, Y., Gramig, B. M., Ranjan, P., & Singh, A. S. (2019). Adoption of agricultural conservation practices in the United States: Evidence from 35 years of quantitative literature. Journal of Soil and Water Conservation, 74(5), 520–534. https://doi.org/10.2489/jswc.74.5.520

Pujos, A., & Morard, P. (1997). Effects of potassium deficiency on tomato growth and mineral nutrition at the early production stage. Plant and Soil, 189(2), 189–196. https://doi.org/10.1023/A:1004263304657

R Core Team (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Radicetti, E., Campiglia, E., Marucci, A., & Mancinelli, R. (2017). How winter cover crops and tillage intensities affect nitrogen availability in eggplant. Nutrient Cycling in Agroecosystems, 108(2), 177–194. https://doi.org/10.1007/s10705-017-9849-7

Ramirez, L. F., E., J., & G., P. (2009). Potassium affects the lycopene and p-carotene concentration in greenhouse tomato. Acta Horticulturae, 821, 223–228. https://doi.org/10.17660/ActaHortic.2009.821.25

Reeve, J., & Drost, D. (2012). Yields and Soil Quality under Transitional Organic High Tunnel Tomatoes. HortScience, 47(1), 38–44. https://doi.org/10.21273/HORTSCI.47.1.38

Reid, J., & Machanoff, C. (2018). Best Management Practices for Long Term Soil Health and Fertility.

Required Agricultural Practices | Agency of Agriculture Food and Markets. (n.d.). Retrieved August 4, 2022, from https://agriculture.vermont.gov/rap

Rittel, H. W. J., & Webber, M. M. (1973). Dilemmas in a general theory of planning. Policy Sciences, 4(2), 155–169. https://doi.org/10.1007/BF01405730

Rivard, C. L., Sydorovych, O., O'Connell, S., Peet, M. M., & Louws, F. J. (2010). An Economic Analysis of Two Grafted Tomato Transplant Production Systems in the United States. HortTechnology, 20(4), 794–803. https://doi.org/10.21273/HORTTECH.20.4.794

Roesch-McNally, G. E., Basche, A. D., Arbuckle, J. G., Tyndall, J. C., Miguez, F. E., Bowman, T., & Clay, R. (2018). The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. Renewable Agriculture and Food Systems, 33(4), 322–333. https://doi.org/10.1017/S1742170517000096

Rogers, EM. (2003). Diffusion of innovations. 5. New York: Free Press; 2003. Free Press.

Rogers, M. A., & Wszelaki, A. L. (2012). Influence of High Tunnel Production and Planting Date on Yield, Growth, and Early Blight Development on Organically Grown Heirloom and Hybrid Tomato. HortTechnology, 22(4), 452–462. https://doi.org/10.21273/HORTTECH.22.4.452

Roques, S. E., Kindred, D. R., Berry, P., & Helliwell, J. (2022). Successful approaches for on-farm experimentation. Field Crops Research, 287, 108651. https://doi.org/10.1016/j.fcr.2022.108651

Rosen, C. J., & Allan, D. L. (2007). Exploring the Benefits of Organic Nutrient Sources for Crop Production and Soil Quality. HortTechnology, 17(4), 422–430. https://doi.org/10.21273/HORTTECH.17.4.422

Rudisill, M. A., Bordelon, B. P., Turco, R. F., & Hoagland, L. A. (2015). Sustaining Soil Quality in Intensively Managed High Tunnel Vegetable Production Systems: A Role for Green Manures and Chicken Litter. HortScience Horts, 50(3), 461–468. https://doi.org/10.21273/HORTSCI.50.3.461

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

Sattar, R. S., Wang, S., Muqadas, M., Ashraf, M. F., & Tahir, M. N. (2017). Qualitative and quantitative approaches to study adoption of sustainable agricultural practices: A research-note on mixed method approach. In International Journal of Agricultural Extension and Rural Development (Vol. 5, Issue 2).

Schattman, R. E., Hurley, S. E., Greenleaf, H. L., Niles, M. T., & Caswell, M. (2020). Visualizing Climate Change Adaptation: An Effective Tool for Agricultural Outreach? Weather, Climate, and Society, 12(1), 47–61. https://doi.org/10.1175/WCAS-D-19-0049.1

Schattman, R. E., Méndez, V. E., Merrill, S. C., & Zia, A. (2018). Mixed methods approach to understanding farmer and agricultural advisor perceptions of climate change and adaptation in Vermont, United States. Agroecology and Sustainable Food Systems, 42(2), 121–148. https://doi.org/10.1080/21683565.2017.1357667

Schattman, R., Jean, H., Faulkner, J., Maden, R., Grubinger, V., McKeag, L., Nelson, K., Erich, M., Burnett, S., & Ohno, T. (2023). Effects of irrigation scheduling approaches on soil moisture and vegetable production in the Northeastern U.S.A. Agricultural Water Management, 287, 108427. https://doi.org/10.1016/j.agwat.2023.108428

Schimel, J. P. (2018). Life in Dry Soils: Effects of Drought on Soil Microbial Communities and Processes. Annual Review of Ecology, Evolution, and Systematics, 49(1), 409–432. https://doi.org/10.1146/annurev-ecolsys-110617-062614

Schipanski, M. E., Barbercheck, M., Douglas, M. R., Finney, D. M., Haider, K., Kaye, J. P., Kemanian, A. R., Mortensen, D. A., Ryan, M. R., Tooker, J., & White, C. (2014). A framework for evaluating ecosystem services provided by cover crops in agroecosystems. Agricultural Systems, 125, 12–22. https://doi.org/10.1016/j.agsy.2013.11.004

Scholefield, D., & Titchen, N. m. (1995). Development of a rapid field test for soil mineral nitrogen and its application to grazed grassland. Soil Use and Management, 11(1), 33–43. https://doi.org/10.1111/j.1475-2743.1995.tb00493.x

Schröder, J. J., Schulte, R. P. O., Creamer, R. E., Delgado, A., van Leeuwen, J., Lehtinen, T., Rutgers, M., Spiegel, H., Staes, J., Tóth, G., & Wall, D. P. (2016). The elusive role of soil quality in nutrient cycling: A review. Soil Use and Management, 32(4), 476–486. https://doi.org/10.1111/sum.12288

Segura, C., Sun, G., McNulty, S., & Zhang, Y. (2014). Potential impacts of climate change on soil erosion vulnerability across the conterminous United States. Journal of Soil and Water Conservation, 69(2), 171–181. https://doi.org/10.2489/jswc.69.2.171

Sela, S., van Es, H. M., Moebius-Clune, B. N., Marjerison, R., Melkonian, J., Moebius-Clune, D., Schindelbeck, R., & Gomes, S. (2016). Adapt-N Outperforms Grower-Selected Nitrogen Rates in Northeast and Midwestern United States Strip Trials. Agronomy Journal, 108(4), 1726–1734. https://doi.org/10.2134/agronj2015.0606

Seybold, E. C., Dwivedi, R., Musselman, K. N., Kincaid, D. W., Schroth, A. W., Classen, A. T., Perdrial, J. N., & Adair, E. C. (2022). Winter runoff events pose an unquantified continental-scale risk of high wintertime nutrient export. Environmental Research Letters, 17(10), 104044. https://doi.org/10.1088/1748-9326/ac8be5

Shennan, C. (1992). Cover crops, nitrogen cycling, and soil properties in semi-irrigated vegetable production systems. HortScience, 27(7), 749–754.

Sideman, B., Bryant, H., Skinner, M., Sullivan, C. F., Hutton, M., Hoskins, B., & Sideman, E. (2019). Survey of High Tunnel Practices in Northern New England, 2016 & 2019.

Sideman, B., McKeag, L., Smart, A., & Wallingford, A. (2023). New England Vegetable Management Guide. New England Vegetable Guide. https://nevegetable.org/

Sideman, R. G., Hoskins, B., Hutton, M., Bryant, H., & Sideman, E. (2020). Optimizing potassium application in organically-grown high tunnel tomato (Solanum lycopersicum) in the northeastern United States. Acta Horticulturae, 1296, 1085–1092. https://doi.org/10.17660/ActaHortic.2020.1296.137

Skog, K. L., Eriksen, S. E., Brekken, C. A., & Francis, C. (2018). Building Resilience in Social-Ecological Food Systems in Vermont. Sustainability, 10(12), Article 12. https://doi.org/10.3390/su10124813

Smith, M., & Henderson, E. (Eds.). (1998). The Real Dirt: Farmers Tell about Organic and Low-Input Practices in the Northeast (2nd edition). Northeast Region SARE / ACE program.

Snapp, S. S., Swinton, S. M., Labarta, R., Mutch, D., Black, J. R., Leep, R., Nyiraneza, J., & O'Neil, K. (2005). Evaluating Cover Crops for Benefits, Costs and Performance within Cropping System Niches. Agronomy Journal, 97(1), 322–332. https://doi.org/10.2134/agronj2005.0322a

Soil Health Cover Crops. (2023). Retrieved September 25, 2023, from https://www.kelloggs.com/en_US/articles/sustainability/soil-health-cover-crops.html

Springer-Heinze, A., Hartwich, F., Henderson, J. S., Horton, D., & Minde, I. (2003). Impact pathway analysis: An approach to strengthening the impact orientation of agricultural research. Agricultural Systems, 78, 267–285. https://doi.org/10.1016/S0308-521X(03)00129-X

Stott, D. E., & Moebius-Clune, B. N. (2017b). Soil Health: Challenges and Opportunities. In D. J. Field, C. L. S. Morgan, & A. B. McBratney (Eds.), Global Soil Security (pp. 109–121). Springer International Publishing. https://doi.org/10.1007/978-3-319-43394-3_10

Stute, J. K., & Posner, J. L. (1995). Synchrony between Legume Nitrogen Release and Corn Demand in the Upper Midwest. Agronomy Journal, 87(6), 1063–1069. https://doi.org/10.2134/agronj1995.00021962008700060006x

Sullivan, D. M., & Heinrich, A. (2016). Providing organic nutrient management guidance to processed vegetable growers: Oregon Processed Vegetable Commission

Continuing Project Report, 2016. Extension Communications; Oregon State University Extension Service.

Sullivan, D. M., Peachey, E., Heinrich, A., & Brewer, L. J. (2020). Nutrient and soil health management for sweet corn (western Oregon). Extension Communications; Oregon State University Extension Service.

Sullivan, D., Andrews, N., & Brewer, L. (2012). Estimating Plant-Available Nitrogen Release from Cover Crops [Extension Catalog publication]. Extension Communications; Oregon State University Extension Service. https://Extension.oregonstate.edu/catalog/pub/pnw-636-estimating-plant-available-nitrogen-release-cover-crops

Suvedi, M., & Kaplowitz, M. (2016). What Every Extension Worker Should Know. Core Competency Handbook. U.S. Agency for International Development (USAID) project Modernizing Extension and Advisory Services (MEAS) www.meas-Extension.org.

Sweeney, M., & Gailans, S. (2020). Retrieved September 4, 2023, from High-tunnel-tomato-pruning_FINAL.pdf. https://practicalfarmers.b-cdn.net/wp-content/uploads/2021/04/20.H.High-tunnel-tomato-pruning_FINAL.pdf

Tallaksen, J. (2021). What is Agricultural Resilience? University of Minnesota Extension. Retrieved August 24, 2023, from https://wcroc.cfans.umn.edu/about-us/wcroc-news/ag-resilience.

Thongsin, W. (2010). High Tunnels. Maine Organic Farmers and Gardeners. Retrieved August 4, 2022, from https://www.mofga.org/resources/season-Extension/high-tunnels/

Tittonell, P. (2020). Assessing resilience and adaptability in agroecological transitions. Agricultural Systems, 184, 102862. https://doi.org/10.1016/j.agsy.2020.102862

Tong, A., Sainsbury, P., & Craig, J. (2007). Consolidated criteria for reporting qualitative research (COREQ): A 32-item checklist for interviews and focus groups. International Journal for Quality in Health Care, 19(6), 349–357. https://doi.org/10.1093/intqhc/mzm042

USDA, (2021). USDA - National Agricultural Statistics Service—Census of Horticulture. Retrieved October 24, 2023 from https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Census_of_Horticultural_Specialties/index.php.

USDA. (2017). USDA - National Agricultural Statistics Service—2017 Census of Agriculture—Volume 1, Chapter 1: State Level Data. Retrieved August 4, 2023, from https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_State_Level/Vermont/

Utter, A., White, A., Méndez, V. E., & Morris, K. (2021). Co-creation of knowledge in agroecology. Elementa: Science of the Anthropocene, 9(1), 00026. https://doi.org/10.1525/elementa.2021.00026

VAAFM. (2023). Interim Survey Data Highlights Severe Weather Impacts for Vermont Agriculture | Agency of Agriculture Food and Markets. Retrieved September 20, 2023, from https://agriculture.vermont.gov/agency-agriculture-food-markets-news/interim-survey-data-highlights-severe-weather-impacts-vermont

Van Den Bossche, A., De Bolle, S., De Neve, S., & Hofman, G. (2009). Effect of tillage intensity on N mineralization of different crop residues in a temperate climate. Soil and Tillage Research, 103(2), 316–324. https://doi.org/10.1016/j.still.2008.10.019

van den Broek, K. L., Luomba, J., van den Broek, J., & Fischer, H. (2021). Evaluating the Application of the Mental Model Mapping Tool (M-Tool). Frontiers in Psychology, 12, 761882. https://doi.org/10.3389/fpsyg.2021.761882

van Hulst, F., Ellis, R., Prager, K., & Msika, J. (2020). Using co-constructed mental models to understand stakeholder perspectives on agro-ecology. International Journal of Agricultural Sustainability, 18(2), 172–195. https://doi.org/10.1080/14735903.2020.1743553

Vermont Agency of Agriculture Food and Markets. (2016). Required Agricultural Practices. Retrieved August 4, 2022, from https://agriculture.vermont.gov/rap

Voisin, A.-S., Salon, C., Munier-Jolain, N. G., & Ney, B. (2002). Quantitative effects of soil nitrate, growth potential and phenology on symbiotic nitrogen fixation of pea (Pisum sativum L.). Plant and Soil, 243(1), 31–42. https://doi.org/10.1023/A:1019966207970

Vollstedt, M., & Rezat, S. (2019). An Introduction to Grounded Theory with a Special Focus on Axial Coding and the Coding Paradigm. In G. Kaiser & N. Presmeg (Eds.), Compendium for Early Career Researchers in Mathematics Education (pp. 81–100). Springer International Publishing. https://doi.org/10.1007/978-3-030-15636-7_4

Wade, J., Culman, S. W., Gasch, C. K., Lazcano, C., Maltais-Landry, G., Margenot, A. J., Martin, T. K., Potter, T. S., Roper, W. R., Ruark, M. D., Sprunger, C. D., & Wallenstein, M. D. (2022). Rigorous, empirical, and quantitative: A proposed pipeline for soil health assessments. Soil Biology and Biochemistry, 170, 108710. https://doi.org/10.1016/j.soilbio.2022.108710

Wagger, M. G. (1989). Time of Desiccation Effects on Plant Composition and Subsequent Nitrogen Release from Several Winter Annual Cover Crops. Agronomy Journal, 81(2), 236–241. https://doi.org/10.2134/agronj1989.00021962008100020020x

Ward, G. M. (1964). Greenhouse Tomato Nutrition—A Growth Analysis Study. Plant and Soil, August 1964, Vol. 21, No. 1 (August 1964), pp. 125-133 Published by: Springer Stable URL: https://www.jstor.org/stable/42932061.

Warman, P. R. (2005). Soil Fertility, Yield and Nutrient Contents of Vegetable Crops after 12 Years of Compost or Fertilizer Amendments. Biological Agriculture & Horticulture, 23(1), 85–96. https://doi.org/10.1080/01448765.2005.9755310

Warner, K. D. (2008). Agroecology as Participatory Science: Emerging Alternatives to Technology Transfer Extension Practice. Science, Technology, & Human Values, 33(6), 754–777. https://doi.org/10.1177/0162243907309851

Warnke, D. (1983). Greenhouse Growth Media: Testing and Nutrition Guidelines Michigan State University Extension Service MSU Ag Department of Horticulture

Warnke, D. (2011). Recommended Test Procedures for Greenhouse Growth Media. The Northeast Coordinating Committee for Soil Testing. Retrieved October 25, 2023 from https://www.udel.edu/academics/colleges/canr/cooperative-extension/fact-sheets/soil-testing-procedures-northeastern-US/

Weil, R. J., Silva, E. M., Hendrickson, J., & Mitchell, P. D. (2017). Time and Technique Studies for Assessing Labor Productivity on Diversified Organic Vegetable Farms. Journal of Agriculture, Food Systems, and Community Development, 7(4), Article 4. https://doi.org/10.5304/jafscd.2017.074.007

Wells, O. S., & Loy, J. B. (1993). Rowcovers and High Tunnels Enhance Crop Production in the Northeastern United States. HortTechnology, 3(1), 92–95. https://doi.org/10.21273/HORTTECH.3.1.92

Wezel, A., Bellon, S., Doré, T., Francis, C., Vallod, D., & David, C. (2009). Agroecology as a science, a movement and a practice. A review. Agronomy for Sustainable Development, 29(4), 503–515. https://doi.org/10.1051/agro/2009004

Wezel, A., Herren, B. G., Kerr, R. B., Barrios, E., Gonçalves, A. L. R., & Sinclair, F. (2020). Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. Agronomy for Sustainable Development, 40(6), 40. https://doi.org/10.1007/s13593-020-00646-z

White, A., Faulkner, J., Conner, D., Méndez, V., & Niles, M. (2022). “How can you put a price on the environment?” Farmer perspectives on stewardship and payment for ecosystem services. Journal of Soil and Water Conservation, 00041. https://doi.org/10.2489/jswc.2022.00041

White, A., Faulkner, J., Sims, S., Tucker, P., & Weatherhogg, K. (2018). Report of the 2017-2018 New England Adaptation Survey for Vegetable and Fruit Growers. Department of Plant and Soil Science, University of Vermont.

Wickham H, François R, Henry L, Müller K (2022). dplyr: A Grammar of Data Manipulation_. R package version 1.0.10, <https://CRAN.R-project.org/package=dplyr>

Wienhold, B. J., & Halvorson, A. D. (1999). Nitrogen Mineralization Responses to Cropping, Tillage, and Nitrogen Rate in the Northern Great Plains. Soil Science Society of America Journal, 63(1), 192–196. https://doi.org/10.2136/sssaj1999.03615995006300010027x

Williams, M. M. (2008). Sweet Corn Growth and Yield Responses to Planting Dates of the North Central United States. HortScience, 43(6), 1775–1779. https://doi.org/10.21273/HORTSCI.43.6.1775

Wittwer, S. H., & Honma, S. (1979). Greenhouse Tomatoes, Lettuce and Cucumbers. Michigan State University Press.

Wolf, A., & Beegle, D. (2011). Recommended Soil Tests for Macro and Micronutrients. Northeastern Regional Publication No. 493. University of Delaware.

Zotarelli, L., Scholberg, J. M., Dukes, M. D., & Muñoz-Carpena, R. (2008). Fertilizer residence time affects nitrogen uptake efficiency and growth of sweet corn. Journal of Environmental Quality, 37(3), 1271–1278. https://doi.org/10.2134/jeq2007.0460

APPENDIX A – Chapter 2

Additional site information

Table 11. Standard soil test results for each site year

			Modified Morgan (ppm)											
Site year	**SOM(%)**	**pH**	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**	**Mn**	**B**	**Cu**	**Zn**	**Na**	**Al**
CBF-2017	2	6.9	8.4	149	1024	65	7	2.4	3.2	0.2	0.1	0.7	10	33
CBF-2018	3.2	6.6	9.7	113	1122	69	6	2.7	3.4	0.2	0.1	0.8	7	32
GF-2017	2.8	6.5	23.4	71	1424	82	13	2.8	2.9	0.7	0.1	0.7	13	16
HF-2018	2.1	6.9	28.3	75	1185	114	5	2.3	1.4	0.2	0.1	0.5	41	17
IT-2018	2.8	7.1	125	89	1771	110	5	5.2	5	0.3	0.3	2.4	7	7
MFF-2017	3.6	5.7	0.4	18	678	101	6.7	2.1	5.8	0	0.3	0.6	NA	37
OHS-2018	3	6.5	5.9	30	1302	111	6	3.4	3.7	0.2	0.3	1.2	10	12
SCF-2017	5.8	5.7	1.3	179	1501	426	6	8.7	4.1	0.2	0.2	0.6	10	49
SCF-2018	5.6	5.9	9.6	164	1827	533	14	11	7.8	0.2	0.2	0.9	29	55

APPENDIX B – Chapter 4

Interview Protocol A – Individual Farmers[2]

1. Can you please describe your farm for me? (~5 min)

- What are the main items your farm produces?
- How many acres of land do you manage?
- Do you own or lease the land you manage?
- What labels do you use to describe your farm (like organic, conventional, sustainable,
- etc.)?
- How many years have you been farming in total? and at your current location?

2. What does 'soil health' mean to you? (~10 min)

- How did you come to this understanding?
- How has your understanding of soil health changed over time?
- What resources do you rely on for information about soil health?
- Who are the people that influence your soil health management decisions?

3. Can you talk me through how you manage your soil health? (~25 min)

- What practices do you employ to promote soil health?
- What do you consider your most effective soil health practices?
- Where did you learn about these practices?
- How do you know if they're working?
- Are there practices you want to try but can't? why not?
- What are the primary ways you assess soil health?
- Can you walk me through how you use that information?
- How do you utilize soil testing, if at all?
- Do you face challenges implementing soil health practices on your farm?
- What could help you overcome those challenges?

4. CONCEPT SORTING (~20 min)

- Group physical, chemical, biological dimensions of soil health
- Group practices, policies, norms, challenges, support tools…
- Identify relationships / connections between grouped concepts
- "How does X relate to Y"

---

[2] These interview protocols are previously published in Horner, C. (2023). Exploring Potential Domains of Agroecological Transformation in the United States. Graduate College Dissertations and Theses.

Focus Group Protocol – Vegetable Farmers

Grouped mental map analysis (~30 min)

1. Does this mental map reflect how you and your farmer peers discuss soil health?
   - What do we need to change so that this visual reflects your groups' understanding of soil health?

2. What knowledge gaps do you see when you look at this visual?
   - What questions do you have when you look at this?

3. What could shift some of the constraining factors?
   - What would the impact of those shifts be?
   - What would a more robust support network for soil health look like?