Soil Health Testing and Management on Organic Farms in Northern Idaho

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Authorization to Submit Thesis

This thesis of Courtney A. Cosdon, submitted for the degree of Master of Science with a Major in Soil and Land Resources and titled "Soil Health Testing and Management on Organic Farms in Northern Idaho," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

In order to build resilience to climate change, increase long-term sustainability of farming operations and decrease the impacts of our current food production system, the concept of soil health has received renewed attention in recent years. Soil is a vital natural resource with the ability to be degraded. Managing for soil health can not only create more sustainable and productive farming systems, but also increase profitability over longer time scales. Benefits of managing for soil health can include decreased soil erosion, more efficient fertilizer use and higher water holding capacity. Despite the benefits of managing for soil health, there is much confusion regarding how to measure it. Traditional soil tests allow farmers to chemically evaluate soils for nutrients, while newer, more integrative soil health testing combines chemical, biological and physical elements to make a more complete analysis. Farmers in northern Idaho and elsewhere are lacking knowledge of how to select appropriate soil health tests, how the results compare to traditional soil fertility tests, and how to interpret and apply the results. This may be especially true for organic growers, since soil health tests have largely been developed and researched on conventionally managed farmground. This project aims to further increase resources regarding testing for soil health and fertility by 1) assessing the relationships among results from traditional soil fertility tests and those of lesser known soil health tests, 2) conducting a survey to determine current soil testing practices in Idaho and barriers for adoption.

The first chapter of this thesis includes research comparing traditional and lesser studied soil health tests including the Haney Soil Health Test (HSHT) and permanganate oxidizable carbon (POxC) at three organic farms in northern Idaho. Three fertilizer application rates were created utilizing plant available nitrogen (N) extracted with 2M KCl (standard fertility test) and H3A (a component of the HSHT). These treatments (KCl and H3A), were compared to a "farmer standard" which simulated how farmers would apply fertilizer without soil testing. Inorganic N extracted by KCl and H3A were comparable ($R=0.90$, $p<0.001$) and produced similar fertilizer recommendations and crop yields. Permanganate oxidizable carbon was more closely related to the total pool of carbon (C) and could be utilized as a measurement of long-term C storage. Comparisons of traditional soil fertility tests with newer soil health measurements were similar to results reported in previous studies on conventionally managed farms. The second chapter reports on an online survey focused on soil testing practices and barriers, which was distributed to small acreage farmers throughout the state of Idaho. We found that 63% of respondents are soil testing, which was surprising given that most soil testing research and outreach is conducted on conventionally managed farms. The main barriers for farmers who are not soil testing are cost and time. Both farmers who soil test and those who do not, are interested in learning about and performing soil health testing. While the relatively low response rate somewhat limits our ability to extrapolate to the larger population, these results suggest that both new and more experienced farmers have similar questions about soil health test interpretation and finding soil testing strategies that are catered to organically managed soils. Overall, while many of our test comparisons were similar to results in studies of conventionally managed farms, some were not, raising questions about certain soil health tests and their utility on organically managed farms. We now know there is a need and a desire from organic farmers for better soil health/testing resources which are specifically catered to their management styles.

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Dedication

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Chapter 1: Literature Review

Soil Health

Soil health is the capability of the soil to function as a living ecosystem which supports life (Natural Resource Conservation Service, 2019). Healthy soils have the ability to cycle nutrients, store carbon, sustain plant and animal life, allow for water and air movement, and regulate pests and diseases (Doran, 2002; Kibblewhite et al., 2008). In the past century, our understanding of soil has grown beyond that of a medium for producing crops to include the ecosystem goods and services it provides (McBratney et al., 2014). We now understand soil as a vital natural resource with the ability to be degraded (Koch et al., 2013). Degradation of soil, in the form of compaction, erosion, acidification and salinification, decreases its ability to provide services and function properly (McBratney et al., 2014). In recent years, soil degradation caused by historical farming practices has also been recognized to a greater degree (McBratney et al., 2014). Extreme land clearing and practices such as tillage have degraded soil structure and increased erosion, both of which result in decreased soil organic matter (SOM) levels (Reganold et al., 1987; Doran and Zeiss, 2000). It has been estimated that nearly 40% of agricultural land, globally, has been degraded by human use (Oldeman, 1992). Degraded soils decrease our ability to provide for growing populations, filter water, sequester carbon and maintain biodiversity (McBratney et al., 2014). There are alternative methods of food production which are less detrimental to soil and water resources and biodiversity. Moving forward, there must be increased attention on decreasing the negative environmental impacts of food production.

Recently, the concept of soil health has received increased attention. There have been numerous publications highlighting the need for increased consideration of soil health and quality (Kibblewhite et al., 2008; Koch et al., 2013; McBratney et al., 2014; Schonbeck et al., 2017; Zuber and Kladivko, 2018). As research is disseminated, farmers understanding of the connection between soil health and profitability of their operation has expanded (Agdaily, 2019). Conferences such as those held by the Soil and Water Conservation Society bring together researchers and farmers to discuss topics such as barriers for adopting soil health practices and management actions that build SOM, reduce nutrient loss and erosion and foster microbial life, all while increasing profitability for farmers (Agdaily, 2019). The USDA Census of Agriculture, of conventionally managed farms, reported a 50% increase in the use of cover crops from 2012 to 2017, as well as an 8 million acre increase in the use of no-till management techniques (Meyers, 2019), demonstrating interest in conservation and building soil health among farmers. While soil health has recently become more of a focus in conventional agriculture, building healthy soil has been a long-term goal of organic agriculture.

Organic Agriculture

Organic agriculture is a type of production system that relies on ecosystem processes and management, over external inputs (Food and Agriculture Organization, 2019). Research has shown that while conventional agriculture often depends on short-term solutions for solving problems and managing fertility such as the targeted application of herbicides and fertilizers, organic production relies on longer-term, more holistic approaches, such as prioritizing on-farm nutrient cycling and promoting biodiversity (Watson et al., 2002). This approach of maintaining long-term productivity requires knowledge of ecosystem dynamics, which starts with an understanding of the processes regulating nutrient supply within the soil (Watson et al., 2002). Familiarity with soil processes allows for the development of more site-specific management practices that can increase resilience and soil health. Improved knowledge and management for soil health will become even more important as greater pressure is placed on existing organic acreage due to the continually increasing demand for organic produce (Gadermaier et al., 2012).

Retail sales of organic produce continue to grow, providing incentive for U.S. farmers to continue to produce as well as for new farmers to break into the market (United States Department of

Agriculture, 2019). A study by Bouttes et al. (2019), found that conversion of conventionally managed European dairy farms to organic resulted in improved economic efficiency, profitability of workers and reduced reliance on subsidies. The number of farmers working certified organic land is on the rise in the U.S. as well, where there was a 56% increase in certified organic farms from 2011 to 2016 (Bialik and Walker, 2019). According to the Organic Trade Association (OTA), in 2018 organic sales in the U.S. reached $52.5 billion, an increase of 6.3% from 2017 (OTA, 2019). One of the main motives for the growth of organic sales comes from consumer belief that the food is healthier and contains fewer chemical residues (Hughner et al., 2007). Although health is the major reason that most consumers decide to purchase organic food, there is evidence that organic agriculture also provides environmental benefits (FAO, accessed 2019).

Since organic farming does not permit synthetic chemical fertility or pest control measures, biological and cultural methods, such as cover crops, compost additions and crop rotations are utilized. These methods rely more heavily on soil processes to convert organically bound nutrients into plant available forms. Not only do the above-mentioned management practices contribute to soil fertility, but they may promote SOM storage, decreased runoff and erosion, increased microbial activity and diversity (Pimental et al., 2005) and overall increases in soil health (Rigby and Cáceres, 2001). Although most of the practices associated with organic agriculture provide benefits to the soil and the surrounding environment, due to the reduced use of pesticides and herbicides, tillage, which is associated with long-term soil degradation, is commonly used as a control for weeds and pests (Dalal and Mayer, 1986; Havlin et al., 1990).

Tillage breaks down soil structure, promotes erosion and results in decreases in SOM and soil health (Havlin et al., 1990; Baker et al., 2007; Brady and Weil, 2010). Although tillage can negatively affect soil, Delate et al. (2015a) reported that reduced till practices, when coupled with cover crops and composted animal manure (practices common on organically managed farms) can increase carbon sequestration and overall soil quality. The effects of tillage on soil properties and health can be better understood through soil testing. Despite the importance of building soil health and supplying adequate nutrient resources to increase yields, many organic farmers in northern Idaho are not conducting soil testing on a regular basis (DePhelps, University of Idaho Area Extension Education, personal communication).

Soil Testing

Soil testing is a chemical analysis of the "nutrient supplying capability" of soil at the time of sampling (Mahler and Tindall, 1994). Soil testing allows farmers to learn about specific soil properties such as nutrient availability and pH, as well as different characteristics such as SOM and microbial activity, which relate to nutrient storage and availability, and soil health (Phillips, 2014). Soil testing provides information to optimize fertilizer application and therefore crop production, information which may help farmers to reduce potential pollution and runoff as well as save money (Collins, 2012). Soil testing should generally take place every one to three years in order to monitor changes and allow for management action (Collins et al., 2013). There are several different soil tests. More traditional soil fertility tests produce a snapshot of plant-essential macro and micronutrients in the soil at the time of sampling, that act as a guide when making fertilizer recommendations to avoid over or under applying nutrients (Collins, 2012). These soil tests and their subsequent interpretations, used for making fertilizer recommendations, are generally based on multiple years of research correlating test results to recommendations and corresponding crop yields (Phillips, 2014). Generally, these tests and their interpretations are geared towards conventionally managed agriculture. Other, more comprehensive tests can provide a more detailed assessment of soil health. These tests provide knowledge not only on chemical data, but on biological and physical aspects of soil as well and are known as soil *health* tests.

Tests of biological, physical and chemical indicators of soil health are often bundled together by testing labs and are frequently accompanied by a soil test score. The two most common tests are the Cornell Comprehensive Assessment of Soil Health (CASH) and the Haney Soil Health Tool

(HSHT). The CASH test provides information on all three of the major domains (biological, physical and chemical) with four unique measurements from each domain including: soil texture, soil respiration and active carbon (Zuber and Kladivko, 2018). While the HSHT investigates only chemical and biological domains, it provides new techniques for measuring organic carbon and nitrogen as well as a 24-hour microbial respiration test (Haney et al., 2018). For this project, we focus on two relatively new soil health tests, the HSHT and Permanganate Oxidizable Carbon (POxC), and how they relate to soil health on organically managed farms.

Haney Soil Health Tool (HSHT)

The Haney Soil Health Tool was developed 15 years ago by USDA-ARS research scientists and is used by several commercial soil testing labs (Haney et al., 2018). The HSHT was selected for this study because it is of wide interest to farmers (Stockdale et al., 2002) and was designed to target the plant available soil nutrient pool and nutrient cycling processes (Haney et al., 2006), both of which are highly relevant in organic farming fertility management approaches. One component of the HSHT is microbial respiration, which is measured as CO_2 released over a 24-hour incubation period (Solvita Burst test) (Haney et al., 2018). Studies have shown that this CO_2 evolution is correlated to nitrogen mineralization rates (Haney et al., 2015), which can be highly related to fertilizer application rates. The HSHT is somewhat unique in that it includes labile SOM pools and reflects microbial activity (Morrow et al., 2016). Increased microbial activity has been shown to benefit plants in many different ways including influencing nutrient acquisition, growth and development, and susceptibility to disease and stress (Morgan et al., 2005). Haney soil nutrient results are communicated to farmers as part of a ‘soil health score’, which includes water extractable organic carbon and nitrogen and microbial respiration (Ward Laboratories, 2017). The value of the soil health score produced by HSHT has not been fully evaluated (Sullivan, 2015).

The HSHT makes use of an extract (H3A) composed of weak organic acids that is meant to mimic plant root exudates, and more accurately represent the rhizosphere environment and mechanisms through which plants naturally acquire nutrients from the soil (Haney et al., 2018). The theory behind the use of this test, specifically the microbial respiration measurement, allows us to make more accurate fertilizer recommendations by inferring nitrogen mineralization capabilities of the soil (Phillips, 2014; Haney et al., 2018). Although, the relationship between the components of the HSHT test, including the microbial respiration measurement, and the amount of fertilizer required by the crop has not been determined. This test has not been adequately calibrated for making fertilizer recommendations in conventional or organic systems. The POxC test is another soil health test which has been suggested to be a useful soil health indicator in the Inland Pacific Northwest.

Permanganate oxidizable carbon (POxC)

The Permanganate Oxidizable Carbon or POxC test uses potassium permanganate to oxidize the active, or labile, fraction of the SOM pool (USDA, 2014). Soil organic matter is composed of carbon compounds with varying degrees of degradability and includes recalcitrant forms, stable and slow cycling, that do not contribute to nutrient cycling in the short-term (USDA, 2014). Soil organic matter has been shown in multiple studies to be a primary indicator of soil health as it influences water holding capacity, soil structure and processes such as nitrogen mineralization (Lucas and Weil, 2012; Weil et al., 2003). While measuring the total SOM pool is useful because of implications to a wide range of soil functions, POxC measures the fraction of carbon which responds quickly to environmental or management changes and likely relates more to short-term nutrient cycling and availability (Lucas and Weil, 2012). There is, however, some debate in the literature over exactly which pool of carbon POxC most accurately captures (Tirol-Padre and Ladha, 2004; Hurisso et al., 2016). Some researchers suggest that POxC more accurately represents the stable pool of carbon rather than the labile pool (Tirol-Padre and Ladha, 2004; Hurisso et al., 2016; Morrow et al., 2016). Lucas and Weil (2012) suggest that while POxC and total organic carbon (TOC) are useful for predicting crop response to SOM management, the POxC method is quicker and simpler, and that guidelines for use by farmers should be developed. While there have been multiple studies done on the POxC method, few have been conducted in organic systems, where SOM management is fundamental to fertility management (Lucas and Weil, 2012; Culman et al., 2012).

Soil Health Testing in Organic Agriculture

While the HSHT and POxC tests appear to be useful tools due to the fact that they measure labile and plant available pools (Lucas and Weil, 2012; Haney et al., 2015), they have mostly been evaluated in fields managed under conventional practices (Stiles et al., 2011; Culman et al., 2012; Haney et al., 2012, 2015; Lucas and Weil, 2012). While this is not unreasonable, as conventional agriculture makes up the majority of agricultural land in the U.S., it leaves few soil health resources tailored to the needs of organic farmers (Ponisio et al., 2014), a growing demographic in Idaho (Ellis, 2019). Since organic agriculture utilizes different application techniques for nutrients, relies on nutrient mineralization via microbial activity and generally includes more diverse crop rotations, all of which can result in considerable changes to biological properties and therefore soil health, newer soil health tests may be well suited for organic agriculture (Schonbeck et al., 2017). In addition, current soil health tests (CASH, HSHT and POxC) all strongly reflect SOM and biological activity, two factors that often differentiate organically and conventionally managed soils (Pimentel et al., 2005; Phillips, 2014), and are essential to nutrient management. Despite the increasing demand for organic products and acreage, soil testing and soil health testing resources for organic farmers do not appear to be increasing at a comparable rate to those available to conventional farmers, which may limit their use on organic farms.

While it is encouraged, soil testing is not currently required as part of the USDA organic certification process (USDA, 2011). Therefore, many farmers don’t rely on soil testing when making fertilizer applications, but apply by feel or experience (Molnar et al., 2001). By increasing the use of soil testing and soil health testing in organic systems, we can fine tune recommendations and decrease possible nutrient runoff and wasteful fertilizer application, ultimately saving farmers money and resources. Improved nutrient management is of great importance as factors such as climate change and the need to feed the world's growing population are increasing stress on food systems (FAO, accessed 2019; Adams et al., 1990). The recent influx of research into soil health and consequent development of soil health tests are great resources for farmers who will need more precise tools to better manage both short and long-term productivity, although specific research relevant to organic agriculture is needed.

The work described in this thesis provides much needed research on how well the HSHT and POxC tests relate to more standard soil fertility tests on organic farms in northern Idaho. The general approach used in this work will be the comparison of relatively new soil health indicators (HSHT, POxC) to standard tests of soil health and fertility (plant available nitrogen, potentially mineralizable nitrogen and carbon, plant available phosphorous) through on-farm field studies. All indicators will be related to yield and crop quality. Furthermore, we will compare the outcomes of fertilizer application rates based on a standard test (extraction with 2M KCl for plant available nitrogen) and the HSHT test. This thesis also includes a chapter that investigates practices and barriers to adoption of soil testing programs on small acreage, organic (certified and not) farms in Idaho via an online survey. The latter chapter provides a foundation for the design of an effective outreach program to promote soil testing on small-acreage farms in northern Idaho.

Research Goal

The overall goal of this project is to provide farmers, extension educators and other researchers with information about selected soil health tests, with emphasis on the HSHT and POxC, in order to increase sustainable practices linked to soil health, fertility management and soil testing.

Research Objectives

The overall objectives to achieve this goal were to:

1. Conduct a field experiment at three farms to determine the relationship between new soil health tests and standard indicators linked to fertility supply

2. Determine the impact of nitrogen fertilizer rates calculated by a) the standard soil test (KCl extract), b) standard on-farm practices without soil testing and 3) inorganic nitrogen values from the HSHT test (H3A extract) on yield and quality of carrot and beet
3. Conduct a survey to determine the current soil testing programs on small acreage, organic (certified and not) farms throughout Idaho

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Chapter 2: Comparing Soil Health Test Metrics and Traditional Soil Fertility Tests on Organic Farming Systems in Northern Idaho

Abstract

Due to increased interest in long-term sustainability and building resilience to climate change, the concept of soil health has received renewed attention. Organic farmers in northern Idaho, however, are lacking the information required to select appropriate soil health tests and interpret their results. This project aims to further increase resources regarding testing for soil health and fertility by assessing the relationships among results from traditional soil fertility tests and those of lesser known soil health tests. Soil health results were also compared to yields of two crops, carrots and beets. Soil samples were collected and analyzed for traditional and lesser studied soil health tests including the Haney Soil Health Test (HSHT) and permanganate oxidizable carbon (POxC) at three organic farms in northern Idaho. Three fertilizer application rates were determined utilizing plant available nitrogen (N) extracted with 2M KCl or H3A (a component of the HSHT). These treatments (KCl and H3A), were compared to a "farmer standard" which simulated how farmers would apply fertilizer without soil testing. Inorganic N extracted by KCl and H3A were comparable ($R=0.90$, $p<0.001$) and produced similar fertilizer recommendations and beet and carrot yields. Permanganate oxidizable carbon was more closely related to the total pool of carbon (C) and could be utilized as a measurement of long-term C storage. The Haney soil health score was not related to yield and was variable across sites and years. Overall, our comparisons of traditional soil fertility tests with newer soil health measurements, of organically managed soils, were similar to results reported in previous studies of conventionally managed soils.

Introduction

Reliance on on-farm nutrient cycling processes is a hallmark of sustainable organic production (Reganold, 1988; Watson et al., 2002) and mandates that farmers make management decisions based on ecological principles and factors such as biodiversity, biological and chemical cycling and crop rotations (Reganold et al., 1987; Watson et al., 2002). The ecological based management goals of organic farming encourage long-term sustainability and productivity while fostering soil health, and may reduce negative environmental impacts of our current food production system (Tuomisto et al., 2012).

Potential health benefits and the reduction of negative environmental impacts of food production are important to consumers who purchase local and organic foods (Hughner et al., 2007). Demand for organically certified food has steadily risen over the past 14 years (United States Department of Agriculture, 2019). According to the Organic Trade Association (OTA), in 2018 organic sales were more than $50 billion, which is 6.3% higher than the previous year (OTA, 2019). Correspondingly, the number of domestic certified organic operations has increased 300% since 2002 (USDA, 2016). As consumer demand continues to rise, there will be increased pressure on existing organic acreage, which could lead to soil depletion and declines in soil health.

Soil health is defined as the capacity of soil to function as a living ecosystem that supports life (Natural Resource Conservation Service, 2019). Healthy soils have the ability to cycle nutrients, store C, sustain plant and animal life, allow for water and air movement, and regulate pests and diseases (Doran, 2002; Kibblewhite et al., 2008). While many of the management practices used on organically managed farms contribute positively to soil health (Clark et al., 1998; Abbott and Manning, 2015), the lack of synthetic herbicides increases the need for mechanical cultivation (Dalal and Mayer, 1986; Pimentel et al., 1993). Mechanical cultivation results in degradation of soil structure, enhanced soil loss through erosion and decreases in soil organic matter (SOM) over time (Reganold et al., 1987; Doran and Zeiss, 2000). Decreased emphasis on off-farm inputs in organic systems makes SOM management especially critical as organic farmers rely on soil microorganisms and biological processes to provide nutrients for crops. Given the importance of soil health and SOM to productivity on organically managed farms, and the relatively high cost of approved fertilizers, regular soil testing and monitoring are important aspects of management.

Soil testing allows farmers to get a snapshot of the nutrients in their soil at the time of sampling. A soil test is a chemical assessment of “nutrient-supplying capability” of a soil at the point in time when a soil sample is collected (Mahler and Tindall, 1994). Standard and accepted soil nutrient tests have been calibrated to crop response in field studies that often include several fertilizer application rates and site locations (Mahler and Tindall, 1994). These tests can reveal excesses or deficiencies of nutrients, allowing farmers to apply fertilizer in a more efficient manner (Collins et al., 2013). There is a wide range of soil tests available, which may cause confusion to farmers (Sustainable Agriculture Research and Education, 2019). To a large extent, calibration of standard soil nutrient availability tests and soil testing research occurring at land grant universities and federal agencies, has been carried out on conventionally managed farms (Phillips, 2014; Ponisio et al., 2014; National Sustainable Agriculture Coalition, accessed 2019). Since organic farming has different nutrient application strategies, more diversified cropping systems and crop rotations (Phillips, 2014), soil sampling, soil testing and test interpretation should not be treated the same as in conventional systems (Phillips, 2014).

A goal of soil health testing is to create a more comprehensive analysis of the soil, than standard fertility testing, by combining chemical, physical and biological properties (NRCS, accessed 2019). Integrative soil health tests are relatively new, and researchers are currently working on assessing how consistent and sensitive the results are across different climates and soil types in both conventionally and, to a lesser extent, in organically managed systems (Morrow et al., 2016; Chahal and Van Eerd, 2018). Even as soil health tests are being developed, there have been clear benefits to including physical and biological elements to soil analysis. Researchers have found that the HSHT, which includes Solvita CO_2, water extractions and H3A (simulates organic acids in plant roots) extraction methods, assesses biological activity and nutrient availability which are important to organic fertility management (Gunderson, 2019; Haney et al., 2018; Haney et al., 2015). Permanganate oxidizable carbon (POxC) is another example of a soil health test (Morrow et al., 2016) that measures biologically active or labile C rather than the total pool of C, which is mostly unavailable for cycling (Hurisso et al., 2016). POxC has been shown to be sensitive to management practices, cost effective and can be performed on-site (Morrow et al., 2016; Bongiorno et al., 2019).

Despite the demonstrated benefits of soil health testing, farmers may struggle with a lack of information about rapidly evolving tests and how they relate to organic agriculture, both of which can be barriers to adoption of soil health testing programs (Rodriguez et al., 2008). This may be especially true on organically managed farms in northern Idaho, where no published soil health studies have been conducted. The overall objectives of this work were to 1) determine the range of HSHT and POxC values and how these tests relate to standard soil tests across three organic farms in northern Idaho, and 2) determine the impact of utilizing HSHT N values to determine N fertilizer application rates in comparison to the standard (2M KCl extraction) test and typical fertilizer practices used in the absence of soil testing. On-farm adoption of testing for soil health and fertility will help farmers advance their efforts towards growing more sustainable food systems. Improved understanding of how these tests perform and inform management in organic systems may lead to greater adoption of soil testing programs.

Methods and Materials

Research sites

Research was conducted on three certified organic farms in northern Idaho during the field seasons of 2018 and 2019. Two farms in Sandpoint, ID, denoted as Farm 1 (F1) and Farm 2 (F2), and a third farm in St. Maries, ID (F3) were selected. Farms 1 and 2 were approximately 17.5 km apart, and the greatest distance between farms was 177 km (between F1 and F3). Fields sampled on each farm had south facing slopes. Soil testing was not regularly utilized at any of the three farms. Northern Idaho has a xeric climate regime with hot, dry summers and cool, wet winters. St. Maries (F3) has an average annual temperature of 8.7° C, and receives an average of 78 cm rain and 142 cm of snow each year (U.S. Climate Data, 2018). Sandpoint (F1 and F2) receives an average of 86 cm of rain and 147 cm of snow annually and has an annual average temperature of 7.8° (U.S. Climate Data, 2018).

Plot design

A replicated (N=3), randomized complete block plot experiment was created at each site. The main treatment was N fertilizer application rate determined by pre-plant inorganic N values (nitrate (NO_3^-) and ammonium (NH_4^+)) from either a 2M KCl extraction or the Haney H3A extract. The third treatment was the typical fertilization practice used by each grower in the absence of soil testing, which varied among the three sites. Fertilizer treatments were randomly assigned to plots within each replicate block. Two sets of plots were established and planted to either Napoli carrots or Early Wonder Tall Top beets for a total of 18 plots at each site (Figure 2.1). Beets and carrots were selected because they are commonly produced on organic farms in the region, mature in a time frame suitable for the season and can be harvested at one point in time. Individual plots were 2.1 x 1.2 m at both F2 and F3. Due to available equipment and space, individual plots at F1 were 1.95 x 0.6 m. At all sites, a 0.3 m wide buffer was used around each individual plot to isolate fertilizer treatments. Plots were moved between years to avoid any carryover effects of the previous year's treatments.

Soil sampling

Soil samples were collected on April 24th and 26th in 2018 and on April 27th and 30th in 2019, when the sites were snow-free and prior to fertilizing and planting. In each plot at each site, five soil cores (3.5 cm diameter) were randomly collected from the 0-to 30-cm depth and separated into 10 cm increments, then composited, bagged and labeled. Soils were placed in a cooler, transported to the laboratory and maintained at 4° C until analysis. A subsample from each plot was passed through a

4mm sieve for biological analyses. The 4mm sieved soil was used for all analyses, unless otherwise noted. The remainder of each sample was air-dried and sieved to 2mm.

Chemical analyses

Approximately one hundred grams of air-dried soil was sent to Ward Laboratories (Kearney, Nebraska) to be analyzed for the Haney Soil Health Test suite and orthophosphate (Haney et al., 2006; Bray, 1945). Inorganic N was extracted (Mulvaney, 1996) at the University of Idaho Soil Management Laboratory using 40 ml 2M Potassium Chloride and 6 grams of field-moist soil. Nitrate and ammonium concentrations extracted at this time were used to determine N fertilizer needs based on KCl extraction (standard fertility test) fertilizer and as the initial measurement for a 35-day N mineralization study. The standard method of using 2mm sieved, air-dried soil, for NO_3^- and NH_4^+ extraction, was modified in order to meet requirements (4mm sieved, field-moist soil) for the 35-day N mineralization study taking place simultaneously. Concentrations of NO_3^- and NH_4^+ extracted from samples that had been split and sieved to both 2 and 4mm were compared, and no differences were found. Nitrate and ammonium concentrations in extracts were measured colorimetrically using the Lachat QuikChem 8500 Series 2 (Colorado, USA).

Water holding capacity was determined using approximately 6 grams of field-moist soil. The soil was weighed, submerged in DI water, drained for two hours, dried for 24 hours at 105° C and reweighed once cooled (Robertson et al., 1999). Gravimetric water content was determined using approximately 20 grams field-moist soil. Soil was weighed, dried in an oven at 105°C for 24 hours, and weighed again (Robertson et al., 1999). For total organic carbon (TOC) and total nitrogen (TN) analysis, soil was ground to 250 µm and dried at 50° C for 24 hours. Samples were measured by dry combustion in a CNS analyzer (Elementar VarioMax CNS; Hanau, Germany). To determine pH, a 10 gram subsample was used to create a 1:1 (soil:water) solution with triple distilled water (Soil Survey Lab Staff, 2004).

Permanganate oxidizable carbon (POxC) was performed according to the Kellogg Biological Station protocol (Weil, 2003). Analysis was performed in duplicate with systematic triplicates. Eighteen ml of DI water and 2 ml 0.2M Potassium Permanganate ($KMn0_4$) were added to 2.5 grams of air-dried soil. Solution was shaken at 200 rpm for 2 minutes. The solution was allowed to settle before a 0.5 ml subsample was added to 49.5 ml distilled water. The solution was then measured along with four prepared standards on a Genesys IOS UV-Vis Spectrophotometer (Thermo Fisher Scientific, USA). Permanganate oxidizable carbon and the HSHT were performed on the top 10 cm of the soil samples, where the majority of biological activity occurs within the soil (Garcia, 2011). Both soil health tests are generally performed on the top 10 cm of soil (Weil et al., 2003; Morrow et al., 2016).

Carbon and nitrogen mineralization analyses

Carbon (Paul et al., 2001) and N (Keiser et al., 2016) mineralization rates were determined simultaneously 3 to 11 days after sample collection in the field. Soil samples were stored at 4°C until analysis. Eight grams of air-dried soil was added to 50 ml centrifuge tubes, soils were adjusted and maintained at 65% water holding capacity with DI water once a week. Tubes were flushed with CO_2-free air, then incubated for approximately 24 hours at 20° C. After each incubation, CO_2 headspace concentration was measured using the Li-Cor LI-7000 CO_2/H_2O Analyzer (Lincoln, Nebraska). Carbon dioxide concentrations were measured twice a week for the first two weeks, and once a week for the following two weeks for a total of 30 days. Analysis for inorganic N, post incubation, was completed on the 35th day of the experiment using the same pre-mineralization protocol. Extracts were measured on the Lachat QuikChem 8500 Series 2 (Colorado, USA).

Physical analyses

Particle size analysis was determined by the hydrometer method (Soil Survey Staff, 2019). In 2018, SOM content was determined using the loss on ignition (LOI) method adapted from Premrov et al. (2018). Five grams of soil was placed into empty, pre-treated crucibles and heated to 550° C for 6 hours. In 2019, SOM was determined using the Ward Labs protocol in which two grams of soil was dried at 360° for 2 hours and 15 minutes (Ward Laboratories, Inc., 2018). Soil organic matter values based on LOI were used in the fertilizer application rate calculation to replicate data that farmers are likely to have access to.

Fertilization treatments

The three fertilizer treatments were different application rates determined by inorganic N concentrations measured by either 2M KCl or Haney H3A tests. The third treatment was determined via an interview with the farmer, who was asked to apply fertilizer to a plot based on their normal fertilization preferences. The volume of fertilizer used was then extrapolated to all the plots assigned to this treatment. This treatment was meant to simulate application representing the rate that farmers might apply if fertilizing without soil testing. Fertilizer recommendations were based on the general formula:

$$Fertilizer\ N\ needed =$$

$$\begin{pmatrix} N\ required\ by\ crop - (inorganic\ N\ in\ soil\ by\ extraction\ (H3A\ or\ KCl) \\ + \\ N\ mineralized\ from\ SOM) \end{pmatrix}$$

(Equation 1)

Where total N required by the crop, beets or carrots, was based on information found in published fertilizer guides (Mack et al., 2000; Thompson, 2017). Site calculations were adjusted by plot area, depth (0.2 m) and site-specific bulk density. The same organic, OMRI-listed fertilizer (4-6-3) was used for all three treatments.

For KCl and Haney treatments, calculated amounts of the fertilizer were pre-weighed in the laboratory, added to the soil surface in an even distribution and worked into the top inch of the soil. For the “farmer standard” treatment, 1.8 kg of fertilizer was pre-weighed in the laboratory and the appropriate amount, deemed by each farmer, was added to plots and worked into the soil as the other treatments were. The bags were reweighed following application to accurately determine the amount of fertilizer added to each plot. The exact application rate, therefore, varied on each farm based on farmer preference. In the 2019 season, soil in plots that tested low in potassium were supplemented with OMRI-listed Sulfate of Potash (0-0-50), (50% K) based on H3A extractable K values. This was done in an attempt to isolate N treatment differences. Nitrogen mineralization from SOM was not fully accounted for in either H3A or KCl N fertilizer applications in 2018. This caused H3A and KCl fertilizer applications to be artificially high and is the main reason for the difference in application rates between 2018 and 2019.

All fertilizer was applied at the time of planting. Once plots were fertilized, carrot seeds were sown and beets transplanted. Organic Napoli F1 pelleted carrot (*Daucus carota*) seed was directly sown into beds at the recommended rate of one seed per one cm (High Mowing, growing recommendations). To avoid competition with weeds, beets were started in the greenhouse and transplanted in the field (one seedling every three inches) approximately 30 days after seeding. Beet seeds were sown in Sunshine organic potting soil amended with G&B Omri-listed Worm-Gro Earthworm Castings (1:1). Plots were weeded regularly and irrigated to avoid losses due to competition and water stress.

After 21-25 days of growth, beets were thinned to approximately $43/m^2$. After 40-44 days of growth, carrots were thinned to approximately $57/m^2$. Beets were harvested during a three-week interval, upon recommendation from growers, when they were at least 6.35 cm in diameter. Carrots were grown for 90-100 days and harvested at one time. Once harvested, fresh weights were taken of the whole plant, tops and roots.

While fresh, roots were graded for quality using USDA quality parameters. Carrots were graded for color, texture, size, shape and damage (United States Department of Agriculture, 1956). Beets were graded for texture, size, damage and shape (United States Standards for Grades of Beets, 2018). Both crops were placed into market class 1, 2 or unmarketable based on cumulative score.

Plant tissue analysis

Beet and carrot tissues were separated by roots and shoots. Shoots were dried at 70°C for 24 hours or until dry (Martin-Prevel, 1987). Roots were chopped up and freeze-dried at -50°C for 48 hours or until dry to extract water. Once dried, roots and shoots were reweighed. Roots and shoots were ground and sieved to 500µm for determination of C and N content by dry combustion in the CNS analyzer (Elementar VarioMax CNS; Hanau, Germany). This measurement was used to determine plant uptake of N.

Haney Soil Health Test measurement selection

The HSHT results include 42 different measurements, including many different forms of macro and micronutrients extracted by H3A. In this study, six main measurements were compared to traditional fertility tests more commonly used by growers. These measurements, Solvita CO_2, water extractable organic carbon and nitrogen, Haney health score, H3A extracted N and phosphorus (P), were chosen because they are newly available measurements as part of the HSHT, and are of primary interest to researchers who study soil health and testing methods. Researchers are interested in determining how these HSHT measurements relate to more common tests, how to use them most effectively and how consistent they are, spatially and temporally.

The Haney H3A extract contains three weak organic acids: oxalic, malic and citric (Haney et al., 2017). The extract is meant to mimic plant root exudates, and more accurately represent the rhizosphere environment and mechanisms through which plants naturally acquire nutrients from the soil (Haney et al., 2018). Haney et al. (2017), claims that this extract can perform multi-nutrient extractions without jeopardizing accuracy of any one nutrient. Laboratories that perform the HSHT analyze the extract for macronutrients NO_3^--N, NH_4^+-N and PO_4^--P as well as micronutrients Ca, Fe, Al, P, and K (Haney et al., 2018). This may be especially valuable for plant available P extraction, which is influenced by pH and therefore measured with pH-specific extractants. According to Haney et al. (2017), H3A can accurately extract plant available P until around pH 7.7, where it will begin to extract less soil P.

The Solvita CO_2 burst measures CO_2-C released over a 24-hour incubation period, as a measurement of microbial respiration (Haney et al., 2018). Soil is dried and rewetted before incubating in order to simulate optimal conditions. Once soil is dried, it is ground, weighed and rewetted using capillary or bottom-up wetting then incubated for 24 hours at 24°C. Respired CO_2 is either measured utilizing Solvita's CO_2 detector probes or an Infrared Gas Analyzer detection system, depending on the laboratory (Gunderson, accessed 2019; Yost et al., 2018). Readings can range from 0-1000 ppm of CO_2-C, although most do not read above 200 (Gunderson, accessed 2019). The higher the respiration measured, the higher the microbial biomass found in the soil.

Statistical analyses

Data was analyzed using R Version 1.2.5001 (R Core Team, 2017). For all significance tests, a linear model and least squared means analysis were used. In the model, the main treatment had interactions with year and crop. Least squared means were separated using the emmeans package (Lenth, 2019) with p-values adjusted using a Tukey adjustment ($p<0.05$). Correlations were calculated using Pearson and Spearman methods.

Results

General soil properties

Soil at F1 has a loam textural class (50% sand, 41% silt and 9% clay), and is classified as an Alfic Vitrixerand (Soil Survey Staff, 2019). The field studied at F1 has a southern aspect and has been in organic production for 26 years. Soil at F2 (27% sand, 62% silt, 11% clay) is classified as an Andic Fragiudalf (Soil Survey Staff, 2019) and has been in organic production for eight years. Soil at F3 (29% sand, 55% silt, 16% clay) has a silt loam textural class. It is classified as a Vitrandic Humudept (Soil Survey Staff, 2019) and has been used for organic production for six years. Soils at all three farms are influenced by volcanic ash to varying degrees and are Andisols or Andic intergrades.

Soil pH and SOM levels were similar among the three soils (Table 2.1). Extractable NO_3^- and NH_4^+ (KCl) concentrations ranged from 5.9 to 19.4 mg N/kg soil in 2018 and 3.6 to 37.5 mg N/kg in 2019. In 2018, KCl N at F3 was significant lower than at F1 and F2. In 2019, F3 had significantly greater (p<0.001) inorganic N levels than F1 and F2.

Bray P ranged from 20 to 215 mg P/kg soil in 2018 and 12 to 408 mg P/kg soil in 2019. Average values of Bray P for each site are shown in Table 2.2. There was a trend for greater Bray available P at F1 (p<0.001 in both 2018 and 2019) and F3 (p<0.001 in both 2018 and 2019), relative to F2, which has had inconsistent fertilization practices. Available P values were low at F2 according to fertilizer guides (Horneck et al., 2011).

Permanganate oxidizable carbon- range and relationship to other soil tests

Permanganate oxidizable carbon (POxC) (0-10 cm), ranged from 216 to 524 mg POxC/ kg soil across the three farms in 2018. In 2019, the values ranged from 376 to 976 mg POxC /kg soil within the top 10 cm of soil. In both years, POxC values at all three sites were significantly different (p<0.001). Despite the fact that plots in year two were within the same field as in year one (maximum of 9.1 m apart at any one farm), POxC values in year two were 1.8 times greater than in year one at F1, 1.8 times greater at F2, and 1.7 times greater at F3.

In 2018 (R=0.8, p<0.001) and 2019 (R=0.83, p<0.001), POxC was significantly, positively correlated with TOC determined by dry combustion (Figure 2.2) and SOM (R=0.75, p<0.001 in 2018 and R=0.82, p<0.001 in 2019) (Figure 2.3) determined by LOI. Permanganate oxidizable carbon was also positively, significantly related to TN in both 2018 (R=0.67, p<0.001) (Figure 2.4) and 2019 (R=0.53, p<0.001) (Figure 2.5). The relationship between POxC and 30-day carbon mineralization (C min) differed between years. In 2018, the relationship was significant (R=0.51, p<0.001), but in 2019 (R=0.18, p=0.23) it was not (Figure 2.6).

Haney Soil Health Test- range and relationship to standard soil tests

Water extractable organic carbon (WEOC) (0-10 cm) ranged from 99 to 178 mg C/kg soil in 2018 among individual plots. Average WEOC values are shown for each site in Table 2.4. In 2019, WEOC ranged from 123 to 337 mg/kg across farms. The mean WEOC value at F2 was significantly lower than that measured at F1 and F3 in both years of the study ($p<0.05$). Across sites, WEOC values were 1.3 to 1.6 times greater in 2019 than in 2018. In both years, WEOC was highly correlated with WEON ($R = 0.67$, $p<0.0001$ in 2018 and $R=0.93$, $p<0.001$ in 2019), as well as H3A P ($R=0.55$, $p<0.05$ in 2018; $R=0.62$, $p<0.05$ in 2019) (Figures 2.4 and 2.5).

Water extractable organic nitrogen (WEON) ranged from 8.5 to 21.8 mg N/kg soil in 2018 and 8.5 to 29.4 mg N/kg soil in 2019 (Table 2.4). Values of WEON at F1 were significantly higher than those measured at F2 and F3 in 2018 ($p<0.001$). In 2019, F2 had significantly lower mean WEON than did F1 and F3 ($p=0.002$), which were not significantly different from each other. In 2018, WEON was positively correlated with TN ($R= 0.72$, $p<0.001$), H3A inorganic N ($R=0.78$, $p<0.001$), TOC ($R=0.58$, $p<0.001$), Bray P ($R=0.56$, $p<0.001$) and H3A P (0.63, $p<0.001$) (Figures 2.4 and 2.5). In 2019, WEON was positively correlated with H3A P ($R=0.58$, $p<0.001$), H3A N ($R=0.63$, $p<0.001$), pH ($R=0.59$, $p<0.001$) and negatively correlated with TOC ($R=-0.51$, $p<0.001$) (Figures 2.4 and 2.5).

In 2018, values of the H3A inorganic N ranged from 5.9 to 17.8 mg N/kg soil. In 2019, values of the H3A test ranged from 5.9 to 37.4 mg N/kg soil. Haney H3A N was significantly higher at F1 ($p<0.001$) in 2018, and significantly higher at F3 ($p<0.001$) in 2019. Inorganic N values from the Haney H3A extract and the standard KCl extract were significantly and positively correlated in 2018 ($R=0.80$, $p<0.0001$) and 2019 ($R=0.99$, $p<0.0001$) (Figure 2.7). Haney H3A P values ranged from 3 to 209 mg P/kg soil in 2018, and 2 to 104 mg P/kg soil in 2019. In both years, H3A P and Bray P values were significantly different at all farms ($p<0.001$) (Table 2.2). Available P values determined by H3A and Bray were significantly and positively correlated in 2018 ($R=0.93$, $p<0.0001$)

and 2019 ($R=0.91$, $p<0.0001$) (Figure 2.8), although the strength and direction of the relationship was variable within sites (Figures 2.9-2.11).

The Solvita CO_2 test results ranged from 61 to 309 mg C/kg soil in 2018 and 29 to 439 mg C/kg soil in 2019 (Table 2.4). In 2018, there were no significant differences among farms, in 2019 all farms were significantly different ($p<0.001$). Solvita CO_2 was consistent between years at F2, but demonstrated greater temporal variability at F1 and F3. At F1, values in 2019 were roughly half of those measured in year 1. At F3, values in year 2 were approximately double those measured in year 1. In both years, Solvita CO_2 was correlated to 30-day C min ($R=0.42$, $p=0.0015$ in 2018, $R=0.41$, $p=0.0021$ in 2019) (Figure 2.12), highly correlated with the HSHT score ($R = 0.95$, $p<0.0001$ in 2018, $R=0.98$, $p<0.0001$ in 2019) and had an inconsistent relationship with N mineralization ($R=0.24$, $p=0.08$ in 2018, $R=0.8$, $p<0.001$ in 2019) (Figures 2.4 and 2.5).

The HSHT score ranged from 10 to 25 in 2018 and 8 to 33 in 2019. In 2018, there was no significant difference in the HSHT score among farms, all farms were significantly different in 2019 ($p<0.001$). At F1, the majority of HSHT scores were lower in 2019 as compared to 2018. At F2, HSHT scores remained fairly constant during the two years and F3 exhibited large variation in scores, although generally increasing. The HSHT score was positively correlated with WEOC ($R=0.34$, $p=0.012$), H3A inorganic N ($R=0.37$, $p=0.006$), KCl inorganic N ($R=0.49$, $p<0.001$), TOC ($R=0.31$, $p=0.023$), TN ($R=0.37$, $p=0.006$) and negatively correlated with pH ($R=-0.29$, $p=0.04$) in 2018. In 2019, HSHT scores were correlated with several different forms of N: N mineralization ($R=0.76$, $p<0.001$), H3A and KCl inorganic N ($R=0.71, 0.72$, $p<0.001$), TN ($R=0.37$, $p=0.006$), percent clay ($R= 0.81$, $p<0.001$) and negatively correlated with pH ($R=-0.24$, $p<0.08$) and percent sand ($R=-0.77$, $p<0.001$) (Figures 2.4 and 2.5).

Comparison of N fertilizer and yields with and without soil testing

Using a standard fertilization application rate calculation (equation 1), fertilizer N applied based on inorganic N determined by 2M KCl and H3A differed among sites and between years (Table

2.5). At F1, application rates of N between years were significantly different ($p<0.001$). In 2018, N applied to the beet and carrot crops was significantly different for all treatments ($p=0.006$). In 2019, in the beet and carrot crops, H3A and KCl application rates were not significantly different, and the standard treatment resulted in significantly higher applications of N ($p<0.001$). At F2, application rates of N between years were significantly different ($p<0.001$). In 2018, for both crops, all treatments resulted in different amounts of N added through fertilization. In general, H3A inorganic N resulted in the lowest application rates, followed by KCl inorganic N and the highest application of N was in the standard treatment plots. In 2019, in the beet crop, all treatments resulted in significantly different amounts of N added ($p<0.001$). In the carrot crop, N fertilizer application rates determined by KCl and H3A were not significantly different, and the standard practice resulted in the highest application rates. At F3, treatments for N application were significantly different between years ($p<0.001$). In 2018, for both crops, N fertilizer application rates determined by KCl and H3A were not significantly different. The standard treatment was significantly lower ($p<0.001$), followed by H3A N and the highest application of N was in the KCl treatment plots. In 2019, in the beet crop, the standard treatment application rate was significantly higher than KCl and H3A treatments ($p<0.001$). In the carrot crop, H3A and KCl were not significantly different and the standard treatment was significantly higher ($p<0.001$). Generally, if the N application treatments were different, across sites and years, H3A had the lowest application, follow by KCl and the farmer standard had the highest application rate of N. This is the case except at F3 where the standard treatment generally resulted in lower N fertilizer application rates than at F1 and F2.

At F1, the three treatments did not significantly impact yields of either crop in 2018 (Table 2.8). In 2019, in the beet crop, H3A produced significantly lower yields than the standard treatment ($p=0.02$), but there were no significant differences between KCl and H3A treatments. There was no significant difference among treatments in the carrot crop. At F2, in 2018, in the beet crop, there was no significant difference in yield between H3A and KCl treatments, but H3A produced significantly lower yields than the standard treatment (p=0.02). In 2019, there was no significant difference in carrot yield among treatments, and only the standard treatment yields were significantly higher than H3A and KCl yields in the beet crop (p=0.02) (Table 2.9.). In both 2018 and 2019, yields at F3 were not significantly different among N application treatments for either crop.

In both 2018 and 2019, N uptake was not significantly different among treatments for either crop at F1 (Tables 2.8. and 2.9.). At F2 in 2018, there was no significant difference between KCl and H3A treatments, but N uptake for the H3A treatment was significantly lower than the standard treatment in the beet crop (p=0.04). There were no significant differences in N uptake among treatments for the carrot crop. In 2019, there was no significant difference in N uptake between H3A and KCl treatments in the beet crop, but the standard treatment was significantly higher than both H3A and KCl (p<0.001). For the carrot crop, N uptake in the standard treatment was significantly higher than in the KCl treatment (p=0.04). In both 2018 and 2019, N uptake was not significantly different among treatments for either crop at F3.

The percent marketable beets and carrots were not impacted by treatments at F1 and F3 in 2018. At F2 in 2018, the standard treatment had a significantly lower percentage of marketable carrots than did H3A and KCl treatments (p=0.03, p=0.01), which were not different from one another (Appendix A.1. and A.2.). In 2019, at F1 and F2 there were significant differences between H3A and the standard treatment in beets (p=0.03, p=0.005), the standard treatment was significantly higher at both farms. There was no difference between H3A and KCl treatments. At F1, there was a significant difference between H3A and standard treatments in carrots (p=0.02), the standard treatment had significantly lower marketability.

Soil health tests and yields

In 2018, total beet yield was positively correlated with WEOC (R=0.47, p<0.001), H3A P (R=0.35, p=0.01) and negatively correlated with POxC (R=-0.56, p<0.001) (Table 2.6). Total carrot yield in 2018, was positively correlated with WEOC (R=0.47, p<0.001), H3A P (R=0.35, p=0.01), and negatively correlated with POxC (R=-0.56, p<0.001) (Table 2.6).

In 2019, total beet yield was positively correlated with WEOC (R=0.54, p<0.001), WEON (R=0.45, p<0.001), H3A N (R=0.46, p<0.001), H3A P (R=0.55, p<0.0001) and negatively correlated with POxC (R=-0.56, p<0.001) (Table 2.6). Total carrot yield in 2019 was positively correlated with WEOC (R=0.72, p<0.001), WEON (R=0.45, p<0.001), H3A N (R=0.46, p<0.001), H3A P (R=0.55, p<0.001) and negatively correlated with POxC (R=-0.56, p<0.001) (Table 2.6).

Discussion

Permanganate oxidizable carbon (POxC)

Given that POxC measures a smaller (approximately 5-20% of total SOM), more labile or active pool of C that is associated with nutrient cycling (Lucas and Weil, 2012; Bongiorno et al., 2019), it is generally viewed as being a more useful tool for nutrient management than is total SOM (Hurisso et al., 2016). In our study, POxC was significantly and positively correlated to TOC (Figure 2.2), SOM (Figure 2.3) and TN in both 2018 and 2019. Correlations between POxC and other indicators of labile C pools were weak and sometimes negative. Permanganate oxidizable carbon and WEOC, for example, were weakly, negatively correlated (R= -0.17, p=0.22) in 2018 and negatively correlated (R=-0.46, p<0.001) in 2019. Permanganate oxidizable carbon and C min were also weakly correlated in 2018 (R=0.51, p<0.001) and 2019 (R=0.17, p=0.23) (Figure 2.6).

Our findings that POxC is more related to total SOM than more labile forms of C, in organically managed soils, are consistent with previously published studies conducted in conventionally managed systems. Hurrisso et al. (2016) found that the relationship between POxC and C min was variable (R^2=0.15-0.80), with significant correlations at nine out of 13 sites studied. The authors of this previous study attributed the variation to different sampling techniques related to sample depth. Tirol-Padre and Ladha (2004) found a lack of correlation between POxC and water-soluble C and microbial biomass C and a strong correlation with TOC (R^2=0.85). Morrow et al.,

(2016) also reported a strong correlation between POxC and total C (R=0.93 p<0.10) and weaker correlations between C min and POxC (R=0.42 to 0.50) on conventionally managed farms in the Palouse region of Idaho.

Traditionally, POxC has been related to labile C, however, newer research relates POxC to the total pool of C with long term storage capabilities. Sprunger et al. (2019), describes POxC as a measurement of “theoretical ‘active C pool’”, as it is related to biological activity and sensitive to management, but also relates to a more processed pool than measurements of labile C, such as C min, and can be indicative of long term C storage. Moving forward, this evidence points to utilization of POxC as a measurement for sequestration of C as it is more closely related to the more stable C pool and is responsive to management. More labile C measurements such as C min or WEOC can be utilized for understanding mineralization and yield potential as they are more closely related to biological measurements (Hurisso et al., 2016).

Haney Soil Health Test

Inorganic nitrogen and phosphorus

There seems to be general consensus among researchers that the HSHT is not well calibrated for different soil types and farming systems and does not provide consistent results or correlate to yield potential (Castro Bustamante and Hartz, 2016; Morrow et al., 2016; Chahal and Van Eerd, 2018). While the majority of these studies have taken place in conventionally managed farming systems, our comparison of the more standard soil tests with the more complex measurements of the HSHT e.g. Solvita CO_2, health score calculation etc. follow a similar trend. Our finding of significant correlation between H3A and KCl extractable N (Figure 2.7), however, is consistent with results reported by Haney et al. (2010). Haney et al. (2010), demonstrated a significant and positive relationship between H3A and 2M KCl inorganic N (R^2= 0.97, p<0.001). Another study by Bavougian et al. (2019), found similar results when comparing KCl extracted NO_3^- with H3A (R^2 = 0.94). Although the values of N differed slightly due to the type of extraction method, based on our results, H3A extracted N reported as part of the HSHT could likely be utilized for making N fertilizer recommendations in these organically managed northern Idaho soils.

Our results for plant available P were seemingly similar to those for N. Inorganic P determined by Bray extraction (traditional test for northern Idaho) was statistically similar to that extracted by H3A in both 2018 ($R=0.93$, $p<0.001$) and 2019 ($R=0.91$, $p<0.001$) (Figure 2.8). Others have also found significant correlations between H3A extracted macro and micronutrients, suggesting that the singular extraction (H3A) may be a suitable replacement for standard tests (Haney et al., 2010; Kaiser et al., 2016; Bavougian et al., 2019). Closer examination of the trends at individual sites, however, suggests substantial variability in the strength, and sometimes direction, of the relationship between Bray and H3A extractable P (Figures 2.9-2.11).

At F3, the relationship between Bray and H3A extracted P was similar between years, although the slope of the linear trend lines varied, the correlations were relatively high in each year ($R=0.82$, $p<0.001$ in 2018 and $R=0.94$, $p<0.001$ in 2019) (Figure 2.11). This same relationship exhibited greater variability between years at F1 and F2. At site F2, Bray and H3A extractable P values were significantly correlated in 2018 ($R=0.51$, $p=0.02$), but were not significantly correlated in 2019 (Figure 2.10). The low levels and narrow ranges of available P at F2 hinders our ability to determine the overall relationship between the two indices of P availability. At F1, Bray P and H3A P were significantly correlated in 2019 ($R=0.91$, $p<0.001$), but not in 2018 (Figure 2.9). Available P values at all sites were also much lower in 2018 relative to those measured in 2019. Soil test data can be variable from year to year and are impacted by environmental conditions and spatial variability within a field (Negassa et al., 2019). The soils in our study were sampled at the same time of year (late April) and received similar amounts of precipitation (rain) between years. Farm 1 and F2 received approximately 75.4 cm of mean annual precipitation in 2018 and 61.2 cm in 2019 (PRISM Climate Group, accessed 2020). Precipitation was 79.2 cm in 2018 and 59.7 cm in 2019 at F3 (PRISM Climate Group, accessed 2020). Similar precipitation values and consistent sampling dates likely minimized variability due to weather. In addition, Lobell et al. (2004) reported that weather variability is not as important as soil variability in terms of fertilizer recommendations.

The 2019 plots in this study were located nearby the 2018 plots (maximum of 9.1 m apart at any one farm), which should have reduced spatial variability. Despite the short distance between plots in successive years, some soil properties were significantly different between years. Haney H3A extractable N, WEOC and WEON, for example, were significantly different between years at all sites. Furthermore, H3A extractable Ca was significantly lower in 2019 than in 2018 at both F1 and F3, and H3A extractable Fe and Al were significantly greater at all sites in 2019 as compared to 2018. Concentrations of Ca, Fe and Al are known to strongly influence the efficacy of standard soil P extractants including Bray, Olsen and Melich-3 (von Wandruszka, 2006; Kovar and Pierzynski, 2009; Wuenscher et al., 2015). The H3A formula was also altered to reduce the extraction of structural Al and Fe (Haney, 2017). Our data suggest that further research should be done across northern Idaho farms to determine how soil type influences the efficacy of H3A to extract available P. To our knowledge, studies comparing H3A to other soil tests for available P in volcanic ash influenced soils are absent from the literature.

Spatial variability and/or field history seem to affect the relationship between these two tests. Haney at al. (2017) states that the best soil tests are consistent across soil type and are therefore, applicable over large geographical ranges. While we cannot definitively determine the cause for the variability, it is most likely due to changes in soil properties at the field scale. Previous studies that report significant correlations between Bray and H3A P only report one year of data (Haney et al., 2017; Chu et al., 2019), indicating the need for more multiyear studies of different soil types to understand this relationship.

WEOC and WEON

Water extractable organic carbon and nitrogen are meant to closely relate to nutrients that are labile or microbially available (Mitchell et al., 2017; Gunderson, 2019). In our study, WEOC/N were weakly correlated with labile sources of nutrients. Water extractable organic carbon and C min had weak and inconsistent relationships (R= -0.21, p=0.13 in 2018; R=0.04, p=0.75). Water extractable organic N and nitrogen mineralization (N min) demonstrated similar inconsistent relationships (R= -0.43, p=0.001 in 2018; R= -0.09, p=0.49). Hargreaves et al. (2019) reported significant correlations between WEOC and active C (R=0.65) and WEON and active C (R=0.62) in organically managed soils. Others have also found correlations between WEOC/N and C min or N min (Haney et al., 2012; Castro Bustamante and Hartz, 2016; Morrow et al., 2016; Mitchell et al., 2017).

In 2018, our study found inconsistent relationships between WEOC and the total pool of C (R=0.06, p=0.63 in 2018 and R=-0.54, p<0.001 in 2019) as well as the more labile pools. Morrow et al. (2016) reported a significant correlation between WEOC and soil organic C (R=0.64) and a weaker relationship between WEOC and 24-day C min test (R=0.31), in Palouse soils. In 2018, WEON and TN demonstrated a strong relationship (R=0.72, p<0.001). In 2019, however, we found only negative correlations between WEON and total and labile N pools. Bustamante and Hartz (2016) reported significant correlations between labile and total pools of N, in a mixture of conventionally and organically managed fields, WEON and TN (R=0.71) and WEON and N min (R=0.62).

While it is accepted that WEOC and WEON are smaller, biologically available fractions of the total pool of C and N in soil (Haney et al., 2012), many researchers have reported correlations between WEOC/N and measures of both labile and total pools of C and N. Our results did not demonstrate clear relationships to either total or labile pools of C and N. Our study suggests that WEOC and WEON do not present consistent relationships with total or labile pools of C and N and more research is necessary to determine the proper use of these measurements.

Solvita CO_2 Burst

The 24-hour Solvita-burst test measures CO_2-C as microbial respiration, which is meant to reflect microbial biomass and potential activity (Gunderson, 2019). Solvita CO_2 results were correlated with those of our 30-day C min measurements (R=0.42, p=0.0015 in 2018; R=0.41,

$p=0.0021$ in 2019) (Figure 2.12). As it is a 24-hour measurement, the Solvita CO_2 test only captures a fraction of the microbial respiration obtained in the 30-day study, however these two measurements were significantly related. While Solvita CO_2 may not be the best representation of microbial activity over longer time frames, it has been used by Haney and others as a measurement for calculating potential N mineralization (Haney et al., 2015; Castro Bustamante and Hartz, 2016; Chu et al., 2019). Haney et al. (2015) found a significant correlation ($R^2=0.82$) between Solvita CO_2 and a 7-day N min test. They concluded that it would be appropriate to utilize Solvita CO_2, as a cheaper and faster method for predicting N min, and making more accurate fertilizer recommendations. In our study, Solvita CO_2 and 35-day N min values were significantly correlated in 2019 ($R=0.8$, $p<0.001$), but not in 2018. Bustamante and Hartz (2016) conducted a study comparing Solvita CO_2 and N min in both organic and conventional systems and found a marginal correlation between the two measurements ($R=0.54$, $p=0.01$). Another study conducted in conventionally managed soils found a weak relationship between these two measurements ($R^{2=}0.19$, $p<0.05$) (Chu et al, 2019). Several studies reported lower correlation coefficients than the original values reported by Haney et al. (2015) and question whether the evidence is robust enough to recommend substitution of the 24-hour Solvita burst test for measurements of N mineralization. Our study resulted in an overall moderate correlation ($R= 0.24$ to 0.80 and $p=0.08$ to 0.001) over the two years of this study. Combining our results with those of previous research suggests that more information is needed to determine the connection between these two measurements and the proper application of Solvita CO_2 test results in organic agriculture fertilizer research.

Haney Health Score

The Haney soil health score combines Solvita CO_2, WEOC and WEON to give farmers an evaluation of their soil's health, with the objective to grow the number over time. It is calculated as:

$$\frac{Solvita\ Burst}{10} + \frac{WEOC}{100} + \frac{WEON}{10} \qquad \text{(Equation 2)}$$

The health score was related to KCl and H3A inorganic N in both years, although the only highly consistent relationship was with the Solvita CO_2 test, which plays a large role in the calculation of the score. In fact, Yost et al. (2018) found that almost all of the variation in the health score is due to the Solvita CO_2 values (R^2=0.98).

Researchers have pointed out that interpretation of the HSHT score is complicated by the fact that its components are mostly labile and therefore highly variable, both temporally and spatially. All of our farms received scores higher than seven, which is the HSHT grade for "healthy" soil, although there was a significant amount of variability. The HSHT value for individual plots at F1 ranged from 10 to 24 in 2018 and 8 to 18 in 2019. The range in HSHT for F2 was 15 to 22 in 2018 and 18 to 28 in 2019. In 2018, the HSHT ranged from 11 to 25 at F3 and 15 to 33 in 2019. The variability of HSHT scores across plots and years at individual sites complicates interpretations and the ability of growers to accurately assess how their management is impacting the value, which is a main goal of the test (Haney et al., 2018).

Comparison of N fertilizer and yields with and without soil testing

Based on this research H3A N and 2M KCl N are comparable and could be utilized interchangeably on organically managed farms in northern Idaho. Additional research is necessary to conclude if this is true on other farms with different soil types and management systems. Fertilizer recommendations based on KCl or H3A inorganic N resulted in different application rates, with H3A generally yielding lower rates of N application, and similar yield and marketability of carrots and beets as well as N uptake. Without soil test data, typically farmers in northern Idaho are over applying N. In our study, there was some evidence of increases in yield with the standard treatment, however, results also demonstrated that this treatment was not always the best for marketability. Over application of N has been shown to result in decreased vitamin C content (Boskovic-Rakocevic et al., 2012) and increased root cracking (Ali et al., 2003) in carrots. Farmers may also be risking nutrient runoff and leaching, while paying for and applying more fertilizer, which could only potentially provide minimum increases in profitability. It is best practice to soil test and obtain the most efficient application rates of nutrients for crop production.

Soil health tests and yields

Permanganate oxidizable carbon was negatively related to beet and carrot yields in 2018 and carrot yield in 2019. Sprunger et al. (2019) reported positive correlations in 3 of 4 sites, with an overall positive correlation between POxC and maize yields ($R=0.52$, $p<0.01$). Culman et al. (2013) also reported positive correlations between grain yields and POxC ($R=0.35$), although the relationship was not statistically significant. Most published studies have found positive correlations between POxC and yield, and found POxC to be a useful indicator of yield potential (Stine and Weil, 2002; Hurisso et al., 2016). Our results of this comparison do not follow trends reported in previously published studies. Most of the previous studies were conducted on conventionally managed systems, our reported negative correlations could be attributed to differences in soil properties such as nutrient cycling or SOM and how they differ in organically managed soils.

Yields were correlated with HSHT test measurements such as WEOC and H3A N and P, however yield did not correlate to the overall HSHT score. Three published studies that compared the HSHT score and yields of mixed annuals, cereal straw and corn and soybeans found no significant correlations (Castro Bustamante and Hartz, 2016; Chahal and Van Eerd, 2018; Chu et al., 2019). Our study reported the same result, for beets and carrots, in both years. Our results demonstrate that the Haney health score is not an indicator of yield, although other elements of the HSHT such as WEOC or H3A N may have potential to be indicators of yield.

Conclusions

Soil health tests help farmers track changes in the soil based on management, although, for a soil health test to be useful to farmers, it needs to be temporally and spatially consistent despite differences in soil type and climatic conditions. To our knowledge, this is one of the first studies utilizing and comparing these soil health indicators on organically managed farms. We found that

HSHT H3A inorganic N is a repeatable and useful measurement for making fertilizer recommendations, when compared to the traditional 2M KCl extraction. The spatial and temporal variability demonstrated by H3A P and Bray P correlations warrants more investigation. The HSHT score did not correlate to yield in either year and was inconsistent from year to year. The overall usefulness of the HSHT score remains unclear. Other aspects of the HSHT, including the Solvita CO_2 demonstrated no clear relationship to either C or N mineralization and require further investigation to determine how the results should be applied to the management of organically managed systems. Our results strongly suggest that POxC is a better indicator of the stable fraction of C, which could be useful to farmers tracking C sequestration, as it is sensitive to management. This finding has been reported in several studies focused on conventionally managed soils as well. While our sample size was small and tested on specific soil types in northern Idaho, our results were largely consistent with the diverse number of studies surrounding these soil health tests.

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Tables and Figures

Table 2.1. Soil (0-30 cm depth) and farm characteristics from the three study sites. Soil organic carbon and pH values are averaged for 2018 and 2019.

Farm	**Soil texture**	**% Slope**	**pH**	**Soil Organic Carbon (%)**	**Years in organic production**	**Soil Subgroup**
F1	Loam	3	6.2	3.9	26	Alfic Vitrixerand
F2	Silt loam	2	5.9	4.3	7	Andic Fragiudalfs
F3	Silt loam	2	6.4	3.1	5	Vitrandic Humudept

Table 2.2. Average Bray and H3A plant available phosphorus. Both Bray P and H3A P values were significantly different at all sites, both years.

Farm	**Bray-P (mg/kg)**		**H3A-P (mg/kg)**	
	2018	**2019**	**2018**	**2019**
F1	161 a	256 a	111 a	78 a
F2	25 c	28 c	1.6 c	2.6 c
F3	79 b	97 b	55 b	49 b

Table 2.3. Average permanganate oxidizable carbon by site in 2018 and 2019. Different letters within a year indicate significant pairwise differences ($p<0.05$).

Farm	**POxC (mg /kg)**	**POxC (mg/kg)**
	2018	**2019**
F1	423 b	744 b
F2	472 a	834 a
F3	296 c	528 c

Table 2.4. Range of values for HSHT measurements studied by farm and year. Unlike lower case letters within a row indicate significant differences across years within an individual site. Unlike capital letters within a column indicate significant differences among sites within a year ($p<0.05$).

Farm	**Haney Health Score**		**Water extractable organic carbon (mg/kg)**		**Water extractable organic nitrogen (mg/kg)**		**Solvita CO_2 (mg/kg)**		**Inorganic N (mg/kg)**		**Inorganic P (mg/kg)**	
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
F1	19.3 Aa	12.6 Aa	149 Aa	231 Ab	17.1 Aa	17.2 Ab	196 Aa	65 Aa	12.8 Aa	9.5 Ab	112 Aa	78 Aa
F2	19.7 Aa	21.3 Ba	130 Ba	174 Bb	13.3 Ba	12.7 Bb	211 Aa	227 Ba	9.3 Ba	8.9 Ab	1.6 Ba	2.3 Ba
F3	19.3 Aa	26.8 Ca	146 Aa	248 Ab	12.9 Ba	19.9 Ab	200 Aa	307 Ca	8.08 Ba	28.2 Bb	55 Ca	50 Ca

Table 2.5. Fertilizer N (kg/ha) applied to beet and carrot plots in 2018 and 2019 and total yield. Different letters within a site and year indicate significant differences (p<0.05). H3A and KCl treatments had no significant impact on the portion of marketable carrots or beets (Appendix A.1. and A.2.).

Farm	**Treatment**	**Fertilizer N applied (kg/ha)**				**Yield (g/plot)**			
		Beets		**Carrots**		**Beets**		**Carrots**	
		2018	2019	2018	2019	2018	2019	2018	2019
F1	H3A	94.4 c	38.9 b	33.7 c	0.0 b	890 a	990 b	1952 a	1184 a
	KCl	121.2 b	59.8 b	72.9 b	5.9 b	1248 a	1231 ab	1743 a	1196 a
	Farmer std.	281.4 a	129.7 a	272.9 a	117.6 a	1299 a	2066 a	2227 a	1645 a
F2	H3A	89.8 c	24.2 c	43.3 c	0.0 b	695 b	472 b	661 a	375 a
	KCl	106.6 b	53.5 b	64.3 b	3.3 b	1017 ab	593 b	602 a	548 a
	Farmer std.	152.9 a	322.9 a	122.1 a	322.9 a	1056 a	1417 a	975 a	538 a
F3	H3A	124.8 a	0.0 b	65.5 a	0.0 b	1814 a	1162 a	2318 a	1950 a
	KCl	146.3 a	2.5 b	77.3 a	0.0 b	2206 a	1421 a	2638 a	1824 a
	Farmer std.	37.4 b	54.1 a	26.5 b	29.4 a	1694 a	1450 a	2694 a	1917 a

Table 2.6. Relationships among soil health measurements, carrot and beet yields, and nitrogen uptake in 2018 and 2019. Correlation coefficients (R) are shown for significant relationships ($p<0.05$). *The F2 beet crop in 2018 had significant damage from pests, which may have influenced correlation results.

Soil health indicator	**Beets***	**Carrots**	**Beets**	**Carrots**
	2018		2019	
POxC	Yield (R= -0.62) %N leaves (R=-0.58) N uptake roots (R= -0.54) N uptake shoots (R= -0.53)	Yield (R= -0.59) %N shoots (R= -0.58) %N roots (R=-0.69) N uptake roots (R= -0.63) N uptake shoots (R= -0.63)	%N roots (R= -0.49) %N shoots (R= -0.50)	Yield (R= -0.80) %N shoots (R= -0.50) %N roots (R= -0.41) N uptake roots (R= -0.77) N uptake shoots (R= -0.80)
HSHT	NS	NS	%N roots (R= 0.46)	%N shoots (R=0.61)
WEON	%N shoot(R= -0.53) %N roots(R= -0.52)	NS	%N shoots (R=0.52) %N roots (R=0.41) N uptake shoots (R= 0.40)	Yield (R=0.68 N uptake shoots (R=0.62) N uptake roots (R=0.68)
WEOC	NS	Yield (R=0.59) %N roots (R=0.52) N uptake shoots (R= 0.58) N uptake roots (R= 0.57)	N uptake shoots (R=0.42) %N shoots (R= 0.41,)	Yield (R=0.72,) N uptake shoots (R=0.65) N uptake roots (R=0.71)
Solvita CO_2	NS	NS	%N roots (R=0.48)	%N shoots (R=0.58)
H3A N	%N shoots (R= -0.49) %N roots (R= -0.52)	NS	%N shoots (R=0.51) %N roots (R=0.60) N uptake roots (R=0.42)	Yield (R=0.46) N uptake shoots (R=0.40) N uptake roots (R=0.50) %N shoots (R=0.61) %N roots (R=0.50)
H3A P	NS	Yield (R=0.52) %N roots (R= 0.41) N uptake roots (R=0.48) N uptake shoots (R= 0.51)	Yield (R=0.39) %N shoots (R=0.45) N uptake shoots (R=0.54)	Yield (R=0.53) N uptake shoots (R=0.48) N uptake roots (R=0.52)

Table 2.7. Amount of fertilizer N added to beet and carrot plots in 2018 and 2019, on a kg/ha basis. Nitrogen was applied to the Haney and KCl plots according to the estimates of pre-plant inorganic N and fertilizer guides for carrots or beets. Standard application is based on the amount of fertilizer added to plots by growers without soil testing. Unlike letters within a column indicate significant differences among treatments within a year ($p<0.05$).

		Carrots		**Beets**	
Farm	**Treatment**	**N applied 2018 (kg/ha)**	**N applied 2019 (kg/ha)**	**N applied 2018 (kg/ha)**	**N applied 2019 (kg/ha)**
F1	H3A	33.7 c	0.0 b	94.4 c	38.9 b
	KCl	72.9 b	5.9 b	121.2 b	59.8 b
	Farmer std.	272.9 a	117.6 a	281.4 a	129.7 a
F2	H3A	43.3 c	0.0 b	89.8 c	24.2 c
	KCl	64.3 b	3.3 b	106.6 b	53.5 b
	Farmer std.	122.1 a	332.9 a	152.9 a	322.9 a
F3	H3A	65.5 a	0.0 b	124.8 a	0.0 b
	KCl	77.3 a	0.0 b	146.3 a	2.5 b
	Farmer std.	26.5 b	29.4 a	37.4 b	54.1 a

Table 2.8. Nitrogen uptake, content and total yield for beets and carrots in 2018. Unlike letters within a column indicate significant differences among treatments (p<0.05).

Farm	**Treatment**	**% N roots**	**% N, leaves**	**N uptake, roots**	**N uptake, leaves**	**Total yield (g)**
Carrots						
F1	H3A	0.72	2.24	178	149	1952 a
F1	KCl	0.80	1.99	183	125	1743 a
F1	Farmer std.	1.05	2.48	293	209	2227 a
F2	H3A	0.54	2.07	41	32	661 a
F2	KCl	0.56	2.04	37	34	602 a
F2	Farmer std.	0.64	2.20	83	74	975 a
F3	H3A	1.16	2.52	300	175	2318 a
F3	KCl	1.19	2.54	365	220	2638 a
F3	Farmer std.	1.19	2.62	378	235	2694 a
Beets						
F1	H3A	1.04	1.79	171	214	890 a
F1	KCl	1.17	2.04	272	310	1248 a
F1	Farmer std.	1.32	2.18	307	409	1299 a
F2	H3A	1.36	1.74	240	135	695 a
F2	KCl	1.66	2.24	303	380	1017 ab
F2	Farmer std.	1.50	2.21	208	292	1056 b
F3	H3A	2.12	3.24	552	807	1814 a
F3	KCl	2.20	3.15	714	857	2206 a
F3	Farmer std.	2.56	3.17	602	678	1694 a

Table 2.9. Nitrogen uptake, content and total yield for beets and carrots in 2019. Unlike letters within a column indicate significant differences among treatments ($p<0.05$).

Farm	Treatment	% N, roots	% N, leaves	N uptake, roots	N uptake, leaves	Total yield (g)
Carrots						
F1	H3A	0.57	2.05	69	74	1184 a
F1	KCl	0.54	2.02	68	68	1196 a
F1	Farmer std.	0.87	2.34	153	145	1645 a
F2	H3A	0.55	2.17	23	22	375 a
F2	KCl	0.56	2.08	33	31	548 a
F2	Farmer std.	0.94	2.74	54	55	538 a
F3	H3A	0.98	3.05	186	212	1950 a
F3	KCl	0.95	2.79	175	182	1824 a
F3	Farmer std.	0.97	2.98	192	216	1917 a
Beets						
F1	H3A	0.90	1.93	125	575	990 a
F1	KCl	1.03	2.39	181	554	1231 ab
F1	Farmer std.	1.07	2.32	323	825	2066 b
F2	H3A	0.86	1.65	72	53	472 a
F2	KCl	0.90	1.71	92	111	593 a
F2	Farmer std.	1.16	2.07	233	619	1417 b
F3	H3A	1.27	2.44	232	438	1162 a
F3	KCl	1.13	2.26	246	474	1421 a
F3	Farmer std.	1.27	2.68	267	749	1450 a

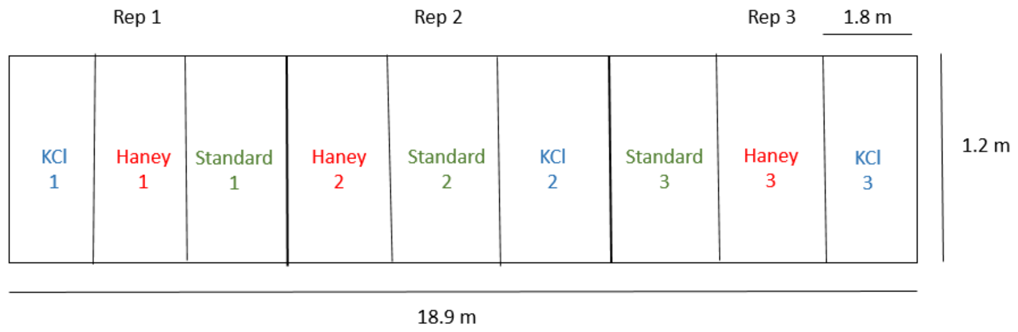

Figure 2.1. Randomized complete block design for fertilizer application treatments for beets or carrots including Haney H3A, KCl inorganic N and a standard fertilizer application used by farmers in absence of soil testing. This design was implemented the three sites, although plots were smaller at F1.

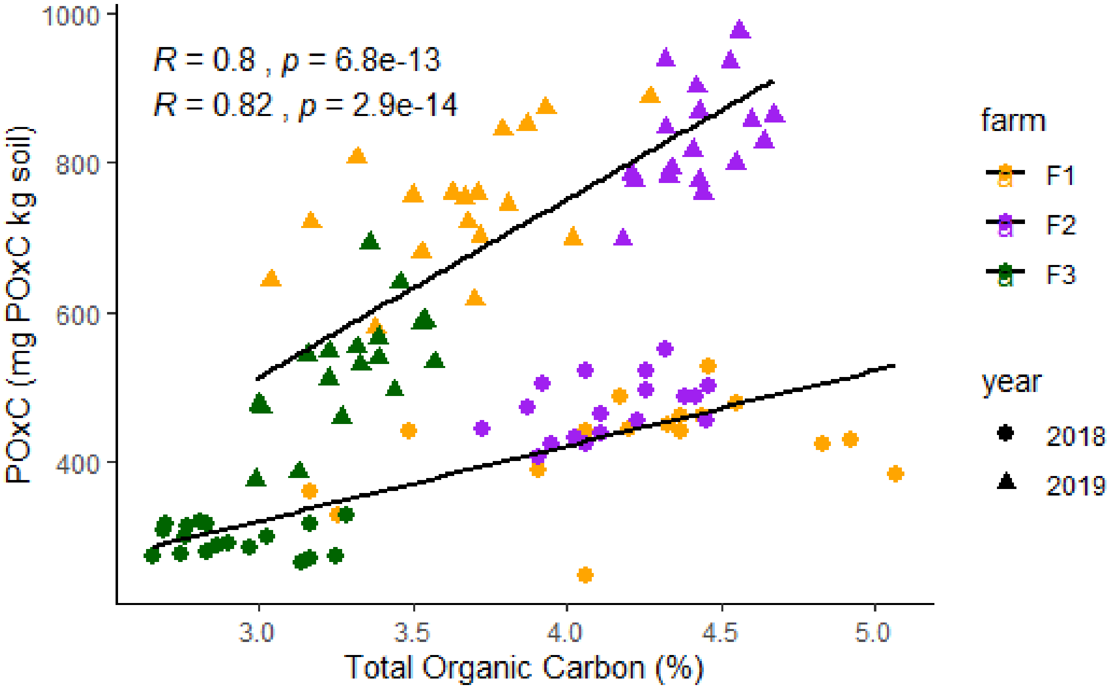

Figure 2.2. Relationship of POxC and TOC, using the Spearman correlation coefficient. Both years, positive, significant relationships were found, (R=0.80 in 2018 and R=0.82 in 2019).

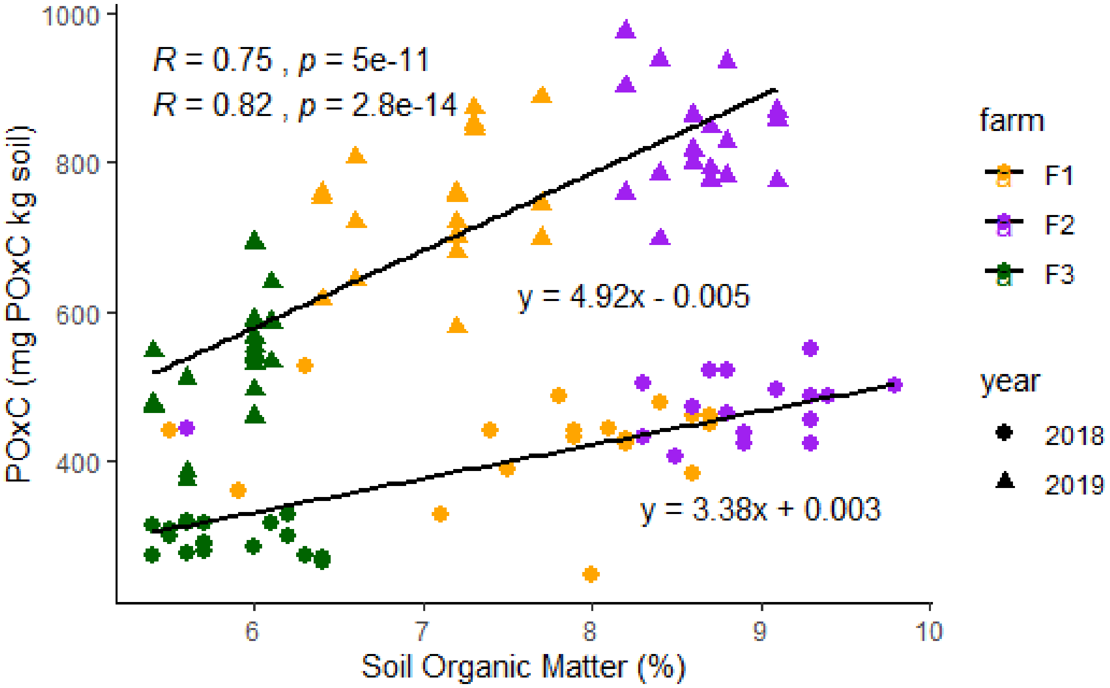

Figure 2.3. Relationship between POxC and SOM, using the Spearman correlation coefficient. Positive and significant relationships were found in both years (R=0.75 in 2018, R=0.82 in 2019).

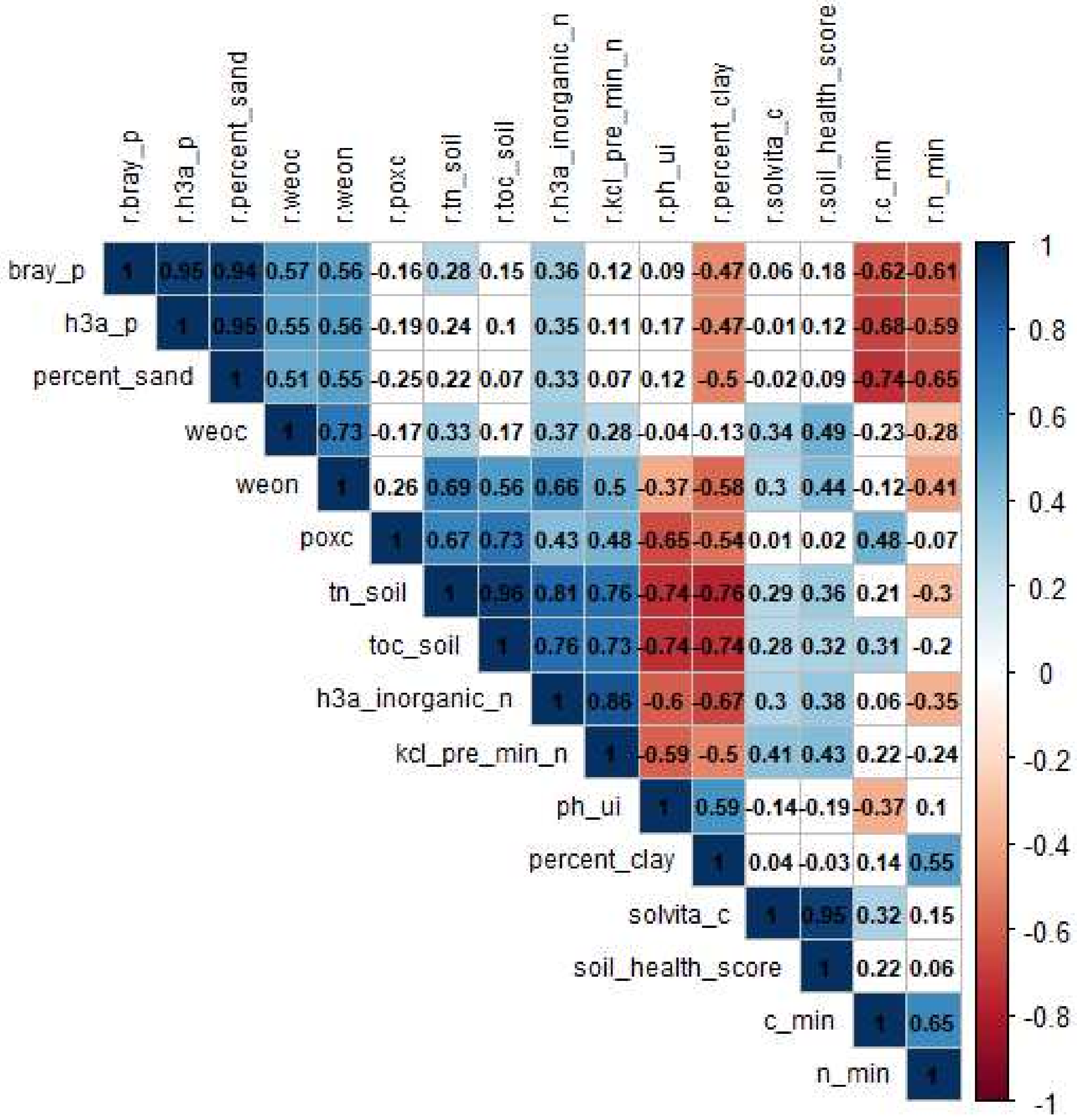

Figure 2.4. Correlation heat map from 2018, displaying relationships among the standard soil tests and the soil health tests (HSHT and POxC) using the Spearman correlation coefficient. Colored squares signify a significant relationship, white squares signify no significant relationship (p>0.05). Positive correlations are in blue and negative correlations are in red. Darker shades indicate a higher correlation coefficient, lighter shades indicate a weaker correlation.

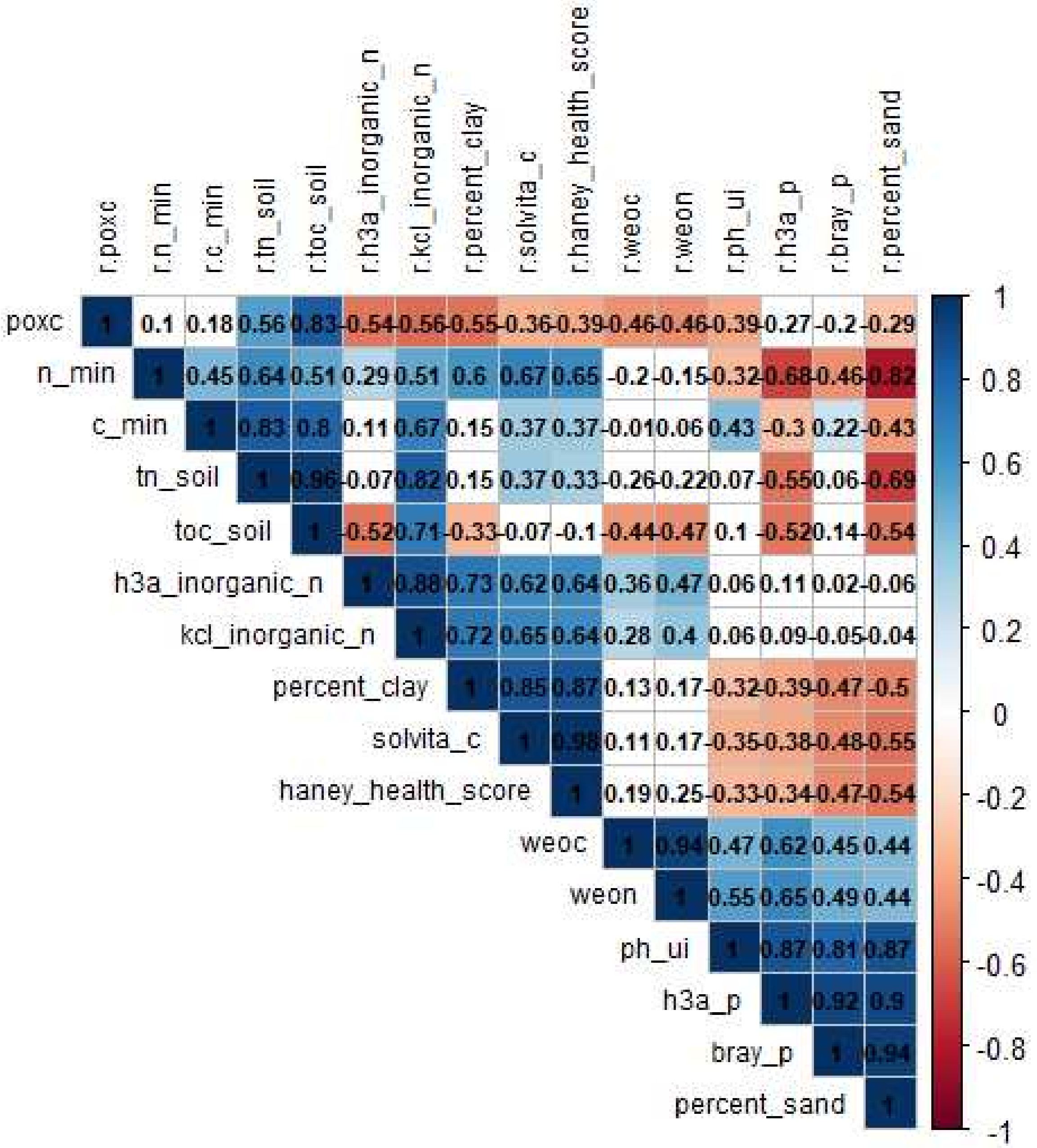

Figure 2.5. Correlation heat map from 2019, displaying relationships among the standard soil tests and the soil health tests (HSHT and POxC) using the Spearman correlation coefficient. Colored squares signify a significant relationship, white squares signify no significant relationship (p>0.05). Positive correlations are in blue and negative correlations are in red. Darker shades indicate a higher correlation coefficient, lighter shades indicate a weaker correlation.

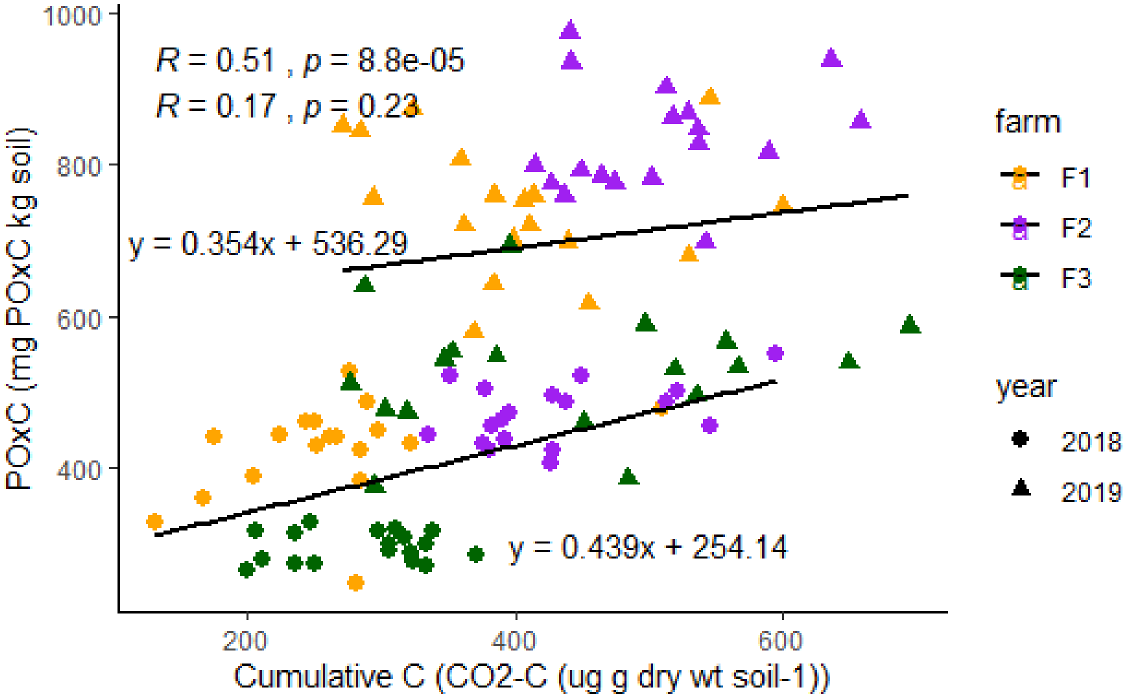

Figure 2.6. Relationship between POxC and 30-day carbon mineralization study (CO_2), using the Spearman correlation coefficient. In 2018, a positive, significant relationship was found (R=0.51). In 2019, the positive relationship was not significant (R=0.17).

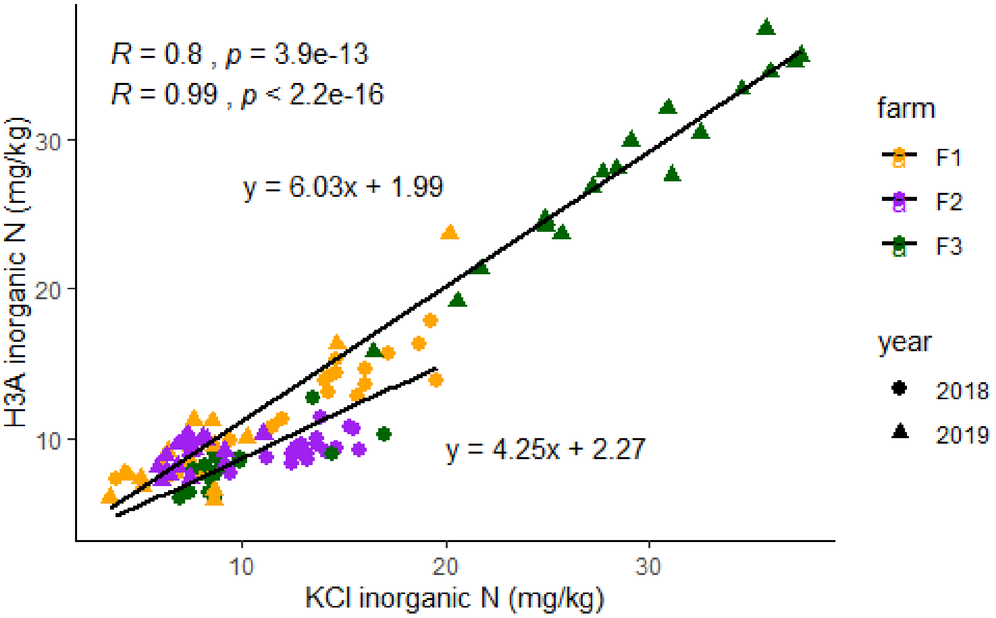

Figure 2.7. Relationship of H3A inorganic N and 2M KCl N, using the Spearman correlation coefficient. Both years there was a positive and highly correlated relationship (R=0.80 in 2018 and R=0.99 in 2019).

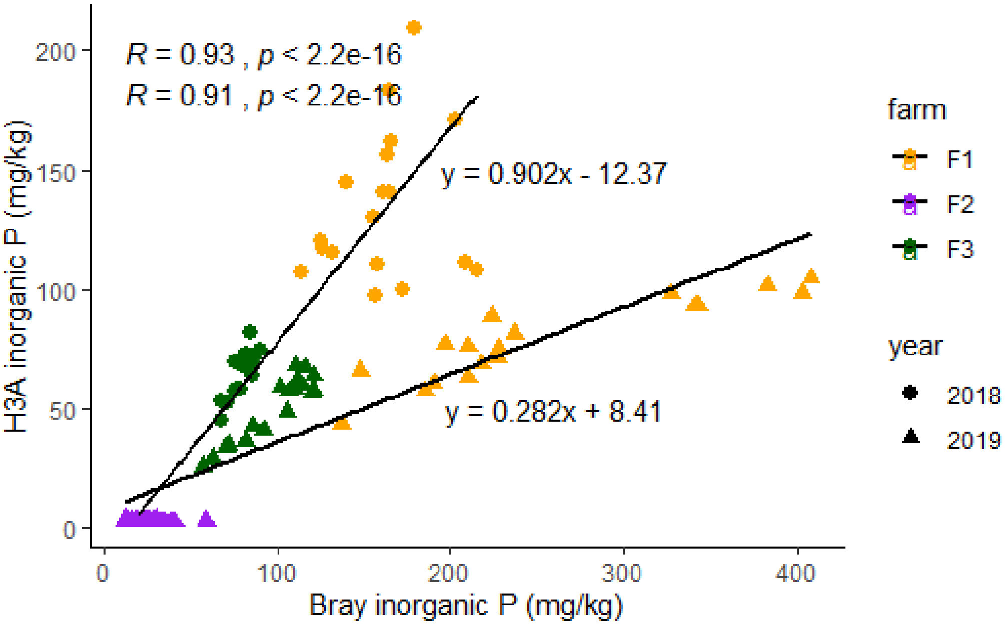

Figure 2.8. Relationship of H3A inorganic phosphorus and Bray inorganic phosphorus, using the Spearman correlation coefficient. Both years there was a positive and highly correlated relationship (R=0.93 in 2018 and R=0.91 in 2019).

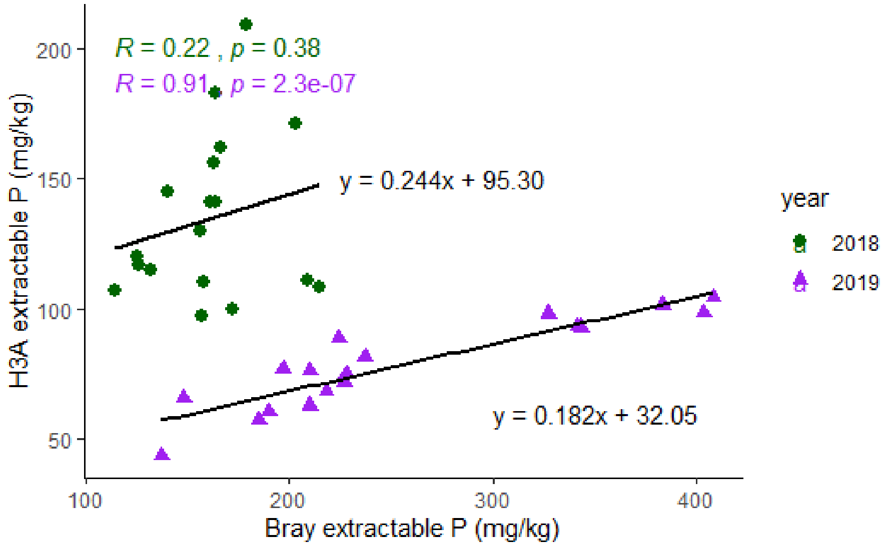

Figure 2.9. Relationship of H3A inorganic phosphorus and Bray inorganic phosphorus at F1 in 2018 and 2019. In 2018, an insignificant relationship was found (R=0.22) between these two variables. In 2019, a positive and highly significant relationship was found (R=0.91).

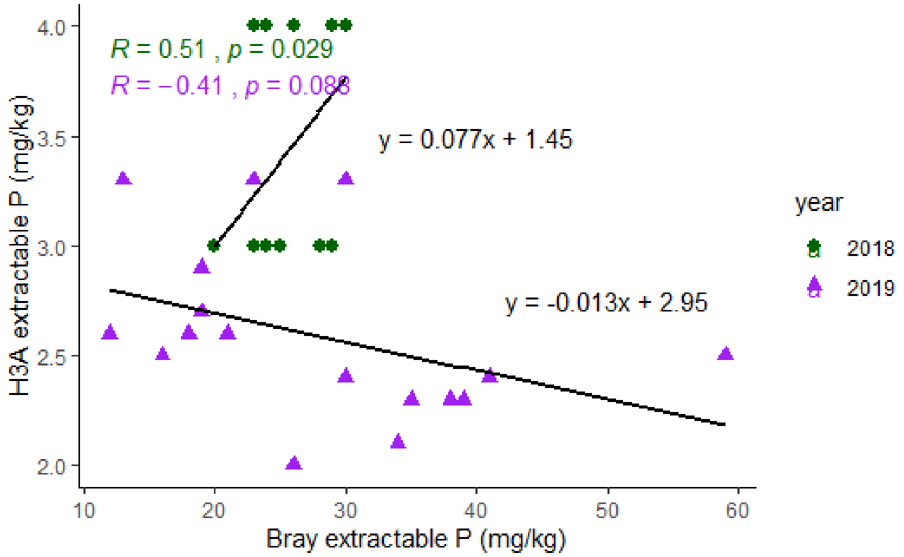

Figure 2.10. Relationship of H3A inorganic phosphorus and Bray inorganic phosphorus at F2 in 2018 and 2019. In 2018, a positive and significant relationship was found (R=0.51). In 2019, a negative and weak correlation was found (R=-0.41).

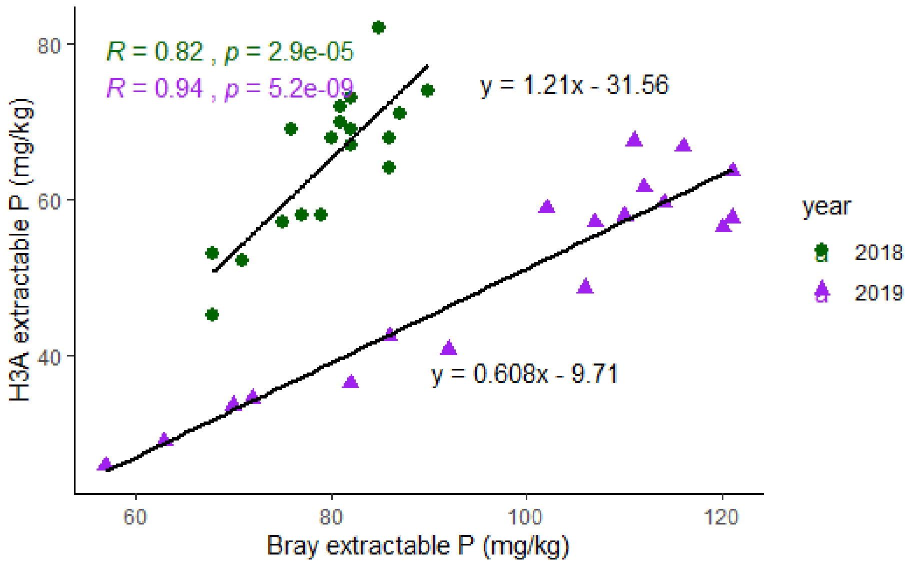

Figure 2.11. Relationship of H3A inorganic phosphorus and Bray inorganic phosphorus at F3 in 2018 and 2019. Positive and significant relationships were found both years (R=0.82 in 2018, R=0.94 in 2019).

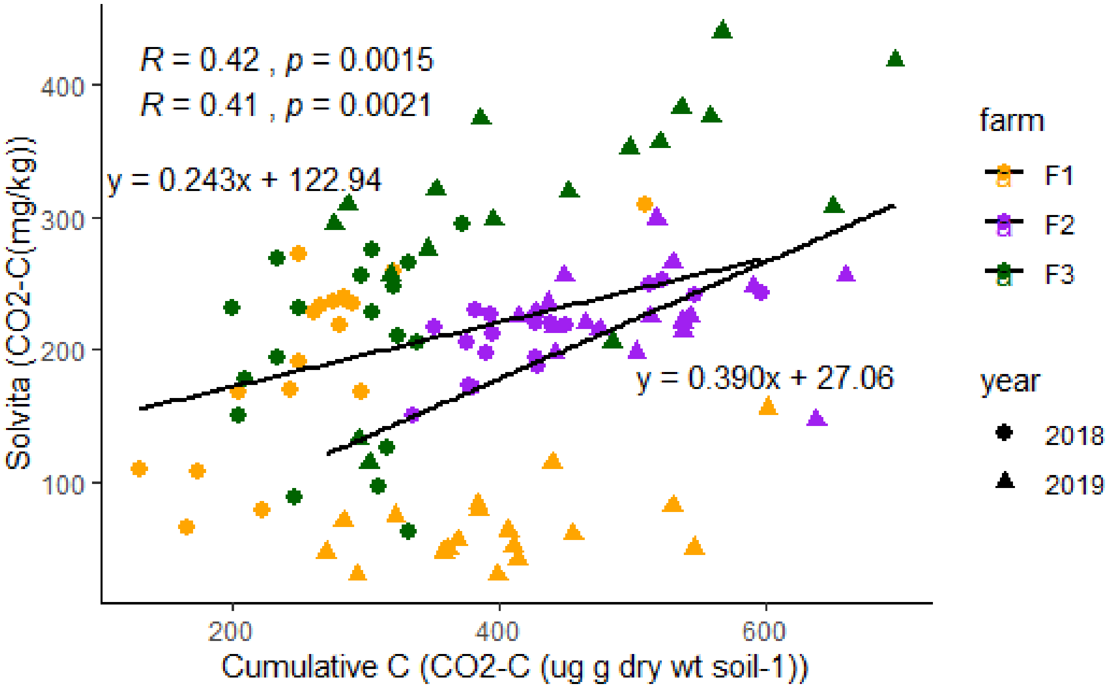

Figure 2.12. Relationship of 24-hour Solvita CO_2 respiration test and 30-day carbon mineralization study, using the Spearman correlation coefficient. There was a positive and significant relationship in both years of this study (R=0.42 in 2018 and R=0.41 in 2019).

Chapter 3: Soil Testing Needs Assessment on Organic Farms in Northern Idaho

Abstract

Managing for soil health can not only decrease soil erosion and runoff of water and fertilizers, but can also increase profitability and production over longer time scales. Traditional soil tests allow farmers to chemically evaluate soils for nutrients, while soil health testing combines chemical, biological and physical elements to make a more complete analysis. Soil health testing may be especially beneficial to organic farmers, given their heavy reliance on microbial activity to supply nutrients to crops. In order to provide effective outreach and education regarding soil testing to organic, small-acreage farmers, more information is needed regarding the extent of soil testing currently being conducted and perceived barriers to adopting soil testing programs. An online survey focused on soil testing was distributed to farmers throughout the state of Idaho. Sixty-three percent of respondents indicated that they are soil testing and doing so frequently (average of 1 out of 2 years). This was surprising given that most soil testing research and outreach is conducted on conventionally managed farms. Both farmers who soil test and those who do not, are interested in learning about and performing soil health testing. There was a correlation between farmers who do not soil test and the length of time they have been farming. While the relatively low response rate somewhat limits our ability to extrapolate to the larger population, these results suggest that both new and more experienced farmers have similar questions about soil health test interpretation and finding soil testing strategies that are catered to organically managed soils.

Introduction

Due to increased interest in long-term sustainability and building resilience to potential disruptors such as climate change, the concept of soil health has received renewed attention (Soil Health Institute, 2019). Soil health is defined as the continued capability of the soil to function as a living ecosystem which supports life (Natural Resource Conservation Service, 2019) and is one of the defining factors of a sustainable farming operation (SARE, 2012). Actively managing for soil health can provide many benefits to production as well as to profitability. Yields, for example can potentially increase by 12% for every 1% increase in soil organic matter (SOM) (SARE, 2019). There are many indicators of soil health including SOM, microbial activity, porosity and nutrient availability (Natural Resource Conservation Service, 2019). Many of these properties can be analyzed by soil tests in order to determine fields, or areas within fields, that require improved management action.

Soil testing is traditionally defined as a chemical analysis of the “nutrient-suppling capability” of a soil at the specific point in time when a soil sample is collected (Mahler and Tindall, 1994). Through research, soil test values are calibrated to crop response, and the documented relationships are used to develop fertilizer rate recommendations (Mahler and Tindall, 1994). The ability to make more accurate fertilizer recommendations is the primary reason that most growers participate in soil testing (Molnar et al., 2001). The growing interest in soil health has created the need to expand our traditional definition of soil testing to focus on a broader suite of properties than just nutrient availability. Soil *health* tests are a comprehensive soil analysis combining physical, biological and chemical aspects that allow farmers to get a more complete picture of what is happening in their soil (Haney, 2013). The benefits of soil health testing include more effective fertilization efforts, optimization of production, decreased nutrient runoff and time and money saved (NRCS, 2009). While components of soil health tests overlap with traditional measures of nutrient supply capacity, results of the two approaches and the various extractants used have not been compared and may be a source of confusion to farmers.

While there are many different resources available for farmers to learn about the benefits and practices of soil testing including Extension publications, University fertilizer guides, Natural Resource Conservation Service guides and commercial lab informational sites, information regarding soil health testing is lacking. This is important given that lack of knowledge is a significant barrier to adoption of soil testing programs on small-acreage farms (Molnar et al., 2001; Uematsu and Mishra, 2010), which are growing in number within the state of Idaho (Ellis, 2019). To our knowledge, no formal efforts have been made to assess the use of soil test routines among small acreage farmers in Idaho.

To most efficiently address the perceived lack of soil health and testing on small-diversified farms in Idaho, we created a survey to obtain a better understanding of the number of farmers currently soil testing, interest in soil health testing and perceived barriers to adoption of soil testing programs. Data from this survey can be utilized to develop efficient outreach programs to provide education and reduce barriers to soil health testing on Idaho small-acreage farms.

Methods and Materials

A survey targeting small-acreage, diversified vegetable farmers throughout the state of Idaho was developed. The goal was to sample farmers who utilize organic methods of production. Farmers included in the survey could hold a certification e.g. certified organic, certified sustainably grown or have no certification. Due to a variety of distribution methods described below, we received three responses from farmers who do not solely utilize organic methods. These responses were included in the results. Participants were recruited in two ways. The USDA Organic Integrity database was utilized to identify Idaho farms growing vegetables. This data base yielded a total of 25 farmer contacts. The survey was also emailed to seven University of Idaho Area Extension Educators, for distribution to their “small farms” email lists. A link to the online survey was emailed to both groups of participants. A reminder was sent to non-respondents three weeks after the initial email. A final reminder was sent out 8 weeks after the first follow-up for a total of three points of contact. Surveys were received from counties throughout the state (Figure 3.1); Boundary, Bonner, Canyon and Ada county had multiple respondents.

Survey design

Qualtrics (Qualtrics, 2002), an on-line survey platform was utilized to gather and analyze responses to the survey questions found in Table 3.1. The survey was organized in two sections. The first included questions regarding soil testing practices, soil laboratory choice and application of results. The second section contained questions about farmer demographics and their land including acreage size, length of ownership and certifications they hold. The survey had 16 questions in total. The final question allowed participants to provide questions for researchers conducting the survey.

The first question of section one, “Do you utilize soil testing on your farm?”, directed respondents to one of two pathways. If the farmers answered yes, they were asked a series of questions including: *how frequently do you soil test?*, *what kind of soil testing do you utilize?*, *how do you apply results of soil tests on your farm?*, etc. If the farmer responded “no”, the questions included: *what is your level of interest in starting a soil testing routine on your farm?, how are you currently making management decisions about soil fertility and health?* Both farmers who answered “yes” and “no” to first question, were asked about perceived barriers related to soil testing.

Results and discussion

While it is a relatively small sample size, this survey gives us some insight about the decision-making process of small acreage farmers in Idaho, regarding soil testing and soil health. The results are especially important given that this survey represents the first research attempt to learn about soil health testing on Idaho small-acreage farms. Twenty-four farmers responded to the survey, and 63% (15) of respondents indicated that they practice soil testing. Nearly half (47%) of the responders who do soil testing indicated that they soil test annually. The other 53% of those who indicated that they soil test, do so every other year (50%) or every 3-5 years (50%). The current recommended rate of testing is every one to three years (Collins et al., 2013).

Eighty-six percent of the farmers that soil test use a commercial lab where they request basic soil tests (86%), while 2 (out of 15) are utilizing soil *health* tests (14%). Basic soil tests are defined here as providing information on plant available nutrients and pH, while soil health tests are a more comprehensive soil analysis and include chemical, physical and biological indicators. The relatively high percentage of small acreage farmers that are currently soil testing is somewhat surprising given that the majority of soil testing research and outreach occur on conventionally managed farms (Ponisio et al., 2014), 2) the relatively high cost of soil testing (Molnar et al., 2001) and 3) the tight profit margins associated with small-acreage systems (Ellis, 2019). In addition to the relatively low response rate, it is also possible that farmers interested in soil testing were more likely to complete the survey, resulting in an artificially high estimate of the current level of soil testing in Idaho.

The two most common soil health tests include the newer Haney Soil Health Test (HSHT) and the Cornell Comprehensive Assessment of Soil Health (CASH). The CASH test provides information on all three of the major domains (chemical, physical and biological) with four unique measurements from each domain including: soil texture, soil respiration and active carbon (Zuber and Kladivko, 2018). While the HSHT investigates only chemical and biological indicators, it provides new techniques for measuring organic carbon and nitrogen as well as a 24-hour microbial respiration test (Haney et al., 2018). While it is not surprising that only two people are requesting soil health tests, which were more recently developed than most standard fertility tests, these tests could be very beneficial to organically managed systems as farmers rely on biological processes in the soil to supply crop nutrition.

Based on responses, most farmers are interpreting soil test results utilizing a combination of sources. The primary source is commercial laboratories (selected by 12 farmers), in conjunction with University fertilizer guides (selected by 4 farmers) or their Extension agents (selected by 4 farmers). Most farmers (73%) who soil test use the information to make decisions regarding fertilizer applications, planting of cover crops or other amendments more precise. Some responses to the question “how do you apply the results of soil tests?” included: “to keep soil healthy”, “make adjustments with soil amendments”, “[soil testing] helps guide our levels of compost and mineral fertilizer applications”, “knowledge for long-term planning” and “to make the most efficient and responsible choices regarding nutrient application in the form of fertilizers, composts or cover crops”.

Nine farmers (37%) who responded to the survey indicated that they do not soil test. All respondents who are not currently soil testing, indicated some degree of interest in starting a soil testing program. Forty-four percent of farmers who are not currently soil testing reported that they were very interested in starting a soil testing routine, 22% reported moderate interest and 33% reported little interest. Most people who don’t soil test are interested in starting a routine, but face barriers.

Most farmers selected more than one barrier to soil testing. The most cited barrier to soil testing among this group was cost (as selected by 4 farmers who do not soil test). Other barriers included time (selected by 3 farmers), lack of information about how to apply results/benefits of testing (selected by 2 farmers) or confusion related to where to send soil for testing (selected by 1 farmer). A few farmers who don’t soil test mentioned that they are still researching soil testing, while others have taken a different approach and use visual clues based on plant appearance to judge what the soil might need. One farmer mentioned relying on field history over soil testing.

Both farmers who soil test and those who don’t, expressed concern that they don’t know how to interpret results from the laboratory. One of the two farmers who utilize both basic and soil health tests indicated that the laboratory they utilize does not provide suggestions or solutions for organically managed farms and the information provided seemed irrelevant to them. While there are numerous guides available (Horneck et al., 2011; Collins, 2012; Collins et al., 2013), most soil test research and calibration is conducted on conventionally managed farms (Phillips, 2014; Ponisio et al., 2014). Extrapolation of this information may be limited by the fact that organically managed soils typically receive greater organic inputs and can differ from those managed using conventional methods (Phillips, 2014). Three responders said they were interested in a specific test (the Haney Soil Health Test) to learn more information about soil microbial populations on their farm. One farmer stated that their local laboratory doesn’t provide services relating to soil health tests. Two farmers who don’t soil test, said they are interested in soil health, but don’t know about the current soil health testing options. While research on soil health tests is relatively new and generally catered to conventionally managed farms, soil health testing might be especially beneficial to organic farmers as they rely heavily on mineralization of nutrients via microbial activity.

Sixty percent of farmers who reported soil testing had a bachelor’s degree or higher. The average age of farmers utilizing soil testing was approximately 50. The average farm size of farmers who use soil testing was 8 acres, and the average years in production was 21 years. Demographics of farmers who do not soil test were similar with an average age of 48, and average farm size of 9 acres. Fifty-five percent of non-soil testing farmers had a bachelor’s degree or higher. The average number of years farming for this group was 8.5 as compared to 21 for the farmers who conduct soil testing. Interestingly, over half of the farmers who are not currently soil testing, have been farming for three years or less, and all farmers who do soil test have been in production for four or more years. The amount of time the land has been in production was the main difference between farmers who soil test and those who do not.

According to this survey, many small-acreage farmers in Idaho already conduct soil testing and do so frequently. The majority of farmers who do not soil test are interested in starting a routine. There are farmers in Idaho who are interested in utilizing soil health tests and require information that is catered to their management system. New guides need to provide information on where to send soil samples for health testing, benefits of soil health testing and interpretation of the results related to organic management.

Conclusions

The main objective of this survey was to gain knowledge of soil testing practices currently used on small acreage farms in Idaho and the barriers to adoption of soil testing programs. We found that many small acreage farmers are conducting soil testing, although more assistance with the interpretation of test results may be warranted. The main barriers to adopting a soil testing program were cost of the tests and time. The Natural Resource Conservation Service (NRCS) offers conservation incentive programs for conventional and organic farmers, but none specifically for small acreage farmers. They also offer a soil quality test kit, which allows farmers to measure chemical, biological and physical soil characteristics themselves (NRCS, 2006). There are agencies who run conservation programs, such as the Soil and Water Conservation Commission and the USDA Farm Service Agency, but not many are specifically tailored to organic farms.

Organic farmers are interested in soil health testing, but need more information about how it relates to their management style. Commercial laboratories need to update and provide information that is catered to farmers utilizing organic management methods. There is a connection between how long farmers have owned the land and their soil testing routine and frequency, suggesting that it may be most effective to target beginning farmers for educational materials. Overall, farmers in Idaho are interested in learning about and conducting soil health testing, but need more information about tests available and interpretation of results that explicitly apply to organic soil fertility.

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Tables and Figures

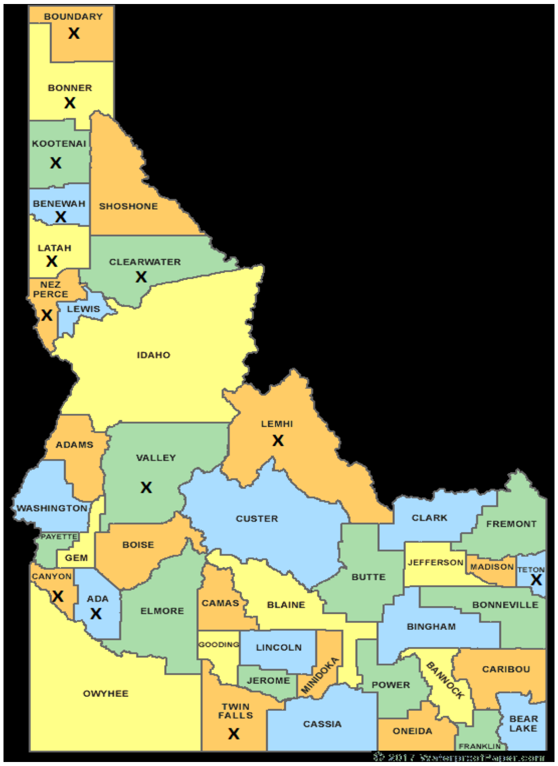

Figure 3.1. Map of Idaho showing the counties with farmers who responded to the survey. Boundary, Bonner, Canyon and Ada county had multiple respondents.

Table 3.1. List of questions on the survey. The first question "Do you utilize soil testing on your farm?" allows for two different pathways based on replies of either yes or no. If respondents answered yes, they would be asked about their soil testing practices. If respondents answered no, they would be asked about the barriers to starting a soil testing regime.

Section	Question #	Question Name	Possible Responses
	1	Do you utilize soil testing on your farm?	Yes, No
1A	2	How frequently do you test your soil?	At least once a year, every other year, every 3-5 years, every 6 or more years
	3	Do you use:	A commercial lab, A store bought kit, Other
	4	What kind of soil testing do you utilize?	Basic soil characteristics (plant available nitrogen, plant available phosphorous, organic matter, pH, etc.) Tests focused on soil health (Haney or CASH tests, infiltration, carbon mineralization, etc.)
	5	Which of the following do you use to help you interpret your soil testing results (mark all that apply)?	Information from the commercial lab I use, My local cooperative extension educator, University of Idaho fertilizer guides, Fertilizer guides from other universities, Soil health or fertility websites, Fertilizer sales company, Other
	6	How do you apply results of soil tests on your farm?	Write in
1B	1	What are the barriers to soil testing for you?	Lack of information on the benefits of soil testing, Lack of information on how to apply result of soil tests, Cost, Time, Other
	2	What is your level of interest in starting a soil testing routine on your farm?	A great deal, A lot, A moderate amount, A little, None at all
	3	How are you currently making management decisions regarding soil fertility and health?	Write in
2 Please tell us a little about yourself and your farm	1	How many years has your farm been in production?	Write in
	2	Do you produce crops using only organic methods?	Yes, No
	3	Which certification(s) do you have for your farm?	Certified organic, certified naturally grown, Other
	4	What size is your farm, in acres?	Write in
	5	What is the highest level of education you have earned?	Some high school or less, high school diploma or equivalent, vocational training, associate degree, some college but no degree, bachelor's degree, some graduate school but no degree, graduate degree
	6	How old are you?	>20, 20-30, 31-40, 41-50, 51-60, 61-70, 71-80, 80+
	7	Which county (or counties) in Idaho is your farm operation located in?	Write in

Appendix

Appendix A.1. Marketability of beets and carrots in 2018, based on USDA quality parameters. Crops were placed into three categories market#1: meaning they are suitable for selling, market#2: meaning they are not suitable for selling, but would be suitable for juicing etc. Non-marketable means that they are not suitable for either e.g. they were too small, extremely deformed or damaged.

2018 Marketability							
		Market #1		**Market#2**		**Non-marketable**	
Farm	**Treatment**	**Carrots**	**Beets**	**Carrots**	**Beets**	**Carrots**	**Beets**
		(----------------------------%------------------------------------)					
F1	H3A	88.1 a	45.8 a	7.3 a	25.0 a	4.6 a	29.2 a
	KCl	90.5 a	37.5 a	7.9 a	41.7 a	1.6 a	20.8 a
	Farmer std.	62.2 a	66.7 a	36.1 a	25.0 a	1.8 a	8.3 a
F2	H3A	97.0 a	45.8 a	3.0 b	8.3 a	0.0 a	45.8 a
	KCl	100.0 a	41.7 a	0.0 b	25.0 a	0.0 a	33.3 a
	Farmer std.	92.9 b	48.2 a	7.1 a	17.9 a	0.0 a	33.9 a
F3	H3A	92.8 a	50.0 a	7.2 a	20.8 a	0.0 a	29.2 a
	KCl	92.4 a	41.7 a	7.6 a	37.5 a	0.0 a	20.8 a
	Farmer std.	85.4 a	58.3 a	11.9 a	8.3 a	2.8 a	33.3 a

Appendix A.2. Marketability of beets and carrots in 2019, based on USDA quality parameters. Crops were placed into three categories market#1: meaning they are suitable for selling, market#2: meaning they are not suitable for selling, but would be suitable for juicing etc. Non-marketable means that they are not suitable for either e.g. they were too small, extremely deformed or damaged.

2019 Marketability							
		Market #1		**Market#2**		**Non-marketable**	
Farm	**Treatment**	**Carrots**	**Beets**	**Carrots**	**Beets**	**Carrots**	**Beets**
		(-----------------------------%-------------------------------------)					
F1	H3A	85.0 a	42.7 b	10.5 b	15.8 b	4.4 b	41.5 a
	KCl	81.5 ab	58.5 ab	12.3 ab	13.1 ab	6.2 ab	28.5 ab
	Farmer std.	60.1 b	68.7 a	34.6 a	17.2 a	5.3 a	14.1 b
F2	H3A	61.1 a	10.2 b	21.6 a	19.7 b	17.3 a	70.1 a
	KCl	64.0 a	19.4 ab	17.0 a	29.8 ab	19.0 a	50.7 ab
	Farmer std.	64.3 a	42.3 a	16.5 a	30.9 a	19.3 a	26.8 b
F3	H3A	87.8 a	37.2 a	11.0 a	22.8 a	1.3 a	40.0 a
	KCl	86.2 a	58.8 a	12.2 a	6.6 a	1.6 a	34.6 a
	Farmer std.	74.9 a	51.8 a	20.8 a	19.0 a	4.3 a	29.1 a

Appendix A.3. Measurements included in the Haney Soil Health Test package.

Measurements included in the Haney Soil Health Test	
	1:1 Soil pH 1:1 Soluble Salts (mmho/cm) Excess Lime Rating Organic Matter (%LOI)
Solvita CO_2 Burst:	Soil Respiration CO_2-C (ppm C)
Water Extract:	Total Nitrogen (ppm N), Organic Nitrogen (ppm N), Total Organic Carbon (ppm C)
H3A Extract:	Nitrate (ppm NO_3-), Ammonium (ppm NH_{4+}), Inorganic nitrogen (ppm N), Total (ICAP) Phosphorus (ppm P), Inorganic (FIA) Phosphorus (ppm P), Organic Phosphorus (ppm P), ICAP Potassium (ppm K), ICAP Iron (ppm Fe), ICAP Zinc (ppm Zn), ICAP Manganese (ppm Mn), ICAP Copper (ppm Cu), ICAP Sulfur (ppm S), ICAP Calcium (ppm Ca), ICAP Magnesium (ppm Mg), ICAP Sodium (ppm Na), ICAP Aluminum (ppm Al)
Calculations:	Microbially Active Carbon (%MAC), Organic C:Organic N, Organic N:Inorganic N, Organic Nitrogen Release (ppm N), Organic Nitrogen Reserve (ppm N), Organic Phosphorus Reserve (ppm P), Organic Phosphorus Release (ppm P)
Soil Health:	Soil Health Calculation, Cover Crop Suggestion
Nutrient Quantity Available for Next Crop:	Nitrogen (lbs N/A), Phosphorus (lbs P_2O_5/A), Potassium (lbs K_2O/A), Nutrient Value ($/A)
Nitrogen Savings by using the Haney Test:	Traditional evaluation (lbs N/A), Haney Test N evaluation (lbs N/A), Nitrogen Difference (lbs N/A), N savings ($/A)