A Dark Laboratory: Exploring Soil Health Perceptions and Assessments in the Maritimes

by

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Abstract

Farmer interviews and soil sampling were conducted on 34 farms to explore how farmers' soil health (SH) perceptions, assessments and management practices relate to lab SH measures: the Cornell Soil Health Assessment (CSHA), bio-indicator *Folsomia candida* growth, and phospholipid fatty acid analysis (PLFA). Farmers emphasized biological and production-based SH aspects but neglected ecological considerations, and their SH assessments agreed most strongly with CSHA assessments of nutrients, available water capacity and biological activity. *F. candida* growth did not differentiate between soils nor reflect CSHA results. Manure application and perennial/mixed rotations were positively correlated with water-stable aggregates, soil respiration, and all PLFA microbial groups, while tillage and simplified grain/vegetable rotations were correlated with P, Cu, Al, sand and the predator:prey ratio. Results show promise for integrating CSHA and PLFA to improve SH assessment, but to affect farmers' SH management decisions, the SH concept and testing must make sense within farmers' worldview.

List of Abbreviations Used

Abbreviation	Definition
µm	micrometer
ACE protein	Autoclaved-citrate extractable protein
AWC	Available water capacity
C	Carbon
CCA	Canonical correspondence analysis
C:N	Carbon to nitrogen ratio
Chem	Soil test results from the PEI Analytical Laboratory
CO_2	Carbon dioxide
CSHA or CSH	Cornell's Comprehensive Assessment of Soil Health
fung	Number of years in which any fungicide was applied
g	Farmer-identified "good" field
herb	Number of years in which any herbicide was applied
insect	Number of years in which any insecticide was applied
K	Potassium
N	Nitrogen
NH_4	Ammonium
NO_3	Nitrate
OM/SOM	Organic matter/Soil organic matter
OSHA	Ontario Assessment of Soil Health
P	Phosphorus
p	Farmer-identified "poor" field
PCA	Principle component analysis
PLFA	Phospholipid fatty acid analysis
PO_4	Phosphate
RDA	Redundancy analysis

SIR	Substrate-induced respiration
SOC	Soil organic carbon
syn_fert	Number of years in which synthetic fertilizers (N, P, K, S) was applied
TON	Total organic nitrogen
WSA	Water-stable aggregates

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> Hard years, of course, come to pines as they do to men … When one pine shows a short year but his neighbours do not, you may safely interpolate some purely local or individual adversity: a fire scar, a gnawing meadowmouse, a windburn, or some local bottleneck in that dark laboratory we call the soil.
>
> Aldo Leopold, *A Sandy County Almanac*

Chapter 1: Introduction

Soil is a dynamic living system whose condition underpins agricultural productivity and ecosystem function (Doran, Sarrantonio & Liebig, 1996). All land-based life on earth, including humanity and its societies, are critically dependent on soil, and its degradation has initiated the downfall of many civilizations in history (Olson, 1981). Given the modern concerns of climate change and the rising global population, extensive research is focused on the question of how to manage our soils to support natural ecosystem functioning and mitigate climate change while simultaneously feeding more people than ever (Janzen, 2006; Powlson et al., 2011).

Globally, soils face significant and diverse threats from land-use change, disturbance and intensive management: soil C loss, nutrient leaching, salinization, acid deposition, heavy metal contamination, erosion, compaction and compromised water storage capacity have all been identified as key challenges (Smith et al., 2016). Each of these factors has complex and cascading effects on a variety of variables in the soil and the surrounding environment. For example, compaction from heavy field traffic has resulted in increased bulk density, decreased porosity, altered nutrient mobility and C and N cycling, reduced root health, and reduced soil biodiversity and microbial biomass (Nawaz, Bourrie & Trolard, 2013). N input to the terrestrial cycle has approximately doubled, largely because of excessive N-fertilization in agriculture, with significant negative impacts on water quality, ecosystem health and soil health (Vitousek et al., 1997).

Soil organic matter (SOM) is widely accepted as a critical component of healthy soils because it is a nutrient source for plants, a stabilizer of the physical soil environment and it

promotes soil biological activity (Goh, 2004). However, conversion from natural to managed landscapes has resulted in an estimated loss of 80-100 Pg C from soils globally (Lal, 1999). Canadian soils have seen similar significant decreases in SOM from cultivation (Smith et al., 1997; Schnitzer et al., 2006). In the Maritimes similar degradative trends have occurred. For example, soil organic C (SOC), C:N ratios, and available P all declined at two soil quality benchmark sites under a corn-forage rotation in the Annapolis Valley through the 1990s (Webb, Wang, Astatkie & Langille, 2000). In PEI, SOM declined at benchmark sites from 1998 to 2015, with highest degradation at intensive agricultural sites (Nyiraneza et al., 2017).

The concept of soil conservation arose as a serious topic of research in the early 1800's in Europe, and became recognized as an urgent task in North America in the 1930's because of catastrophic soil erosion (Dotterweich, 2013). Through the 20th century, researchers became concerned with the topic of 'soil quality', which was largely focused around soil chemical and physical properties to maintain or increase yields. This focus on soil chemistry was mirrored by an increased use of synthetic chemical inputs and a redistribution of the agricultural knowledge base away from the farm to the chemical company, who provided soil management prescriptions (Morgan & Murdoch, 2000).

These widespread changes in on-farm decision making represented a massive cultural shift toward high-intensity management. Intensification is the increase in external inputs, increased scale of operations and simplification of the landscape to increase yields (Shriar, 2000; Stoate et al., 2001). The key practices that are typically used to define management intensity in a variety of studies have also been identified as critical factors affecting the soil. These include the application of herbicides, pesticides and fertilizers, tillage practices, complexity of crop rotation, and the amount of organic matter returned to the soil (Herzog et

al., 2006; Kleijn et al., 2009; Le Féon et al., 2010; Temme & Verburg, 2011; Wilson, Koen, Barnes, Ghosh & King, 2011; Acin-Carrera et al., 2013).

Intense agricultural management is linked with a range of negative trends in soil biology, chemistry and physics. Although intensive management typically involves high application of fertilizers, it often reduces nutrient retention in the soil because of excessive tillage, erosion and reduced SOM (Moebius-Clune et al., 2016). High inorganic N input has a variety of cascading effects on soil biology and the surrounding environment when leaching occurs (Herzog et al., 2006; Kleijn et al., 2009; Le Féon et al., 2010; Temme & Verburg, 2011). N-fertilization causes shifts in the microbial community often leading to bacteria-dominated systems with reduced fungal biomass (Bardgett & McAlister, 1999; De Vries, Hoffland, van Eekeren, Brussaard & Bloem, 2006), although fungal:bacterial ratios are not always affected (Postma-Blaauw, de Goede, Bloem, Faber, & Brussaard, 2010). High land-use intensity also reduces soil biota diversity, decreases biomass of functional groups, and reduces the number of trophic levels (Tsiafouli et al., 2015). The negative effects are particularly evident for large biota such as earthworms, which respond more readily to changes in intensity (Postma-Blaauw et al., 2010; Tsiafouli et al., 2015). Intense management, by reducing plant cover/litter input and increasing disruption of soil aggregates, reduces SOM and SOC (Janzen, 2006; Wander & Nissen, 2004; Acin-Carrera et al., 2013; Wilson et al., 2011).

In terms of physical soil indicators, high intensity tillage, low crop rotation and low OM-input increase bulk density (Wilson et al., 2011), reduce water-stable aggregation and decrease water-holding capacity (Moebius et al., 2007; Acin-Carrera et al., 2013). Small water-stable aggregates are particularly sensitive to management practices (Moebius et al.,

2007). Soil pores greater than 30 μm – representing macro- and meso-pores that are drained by gravity – are also negatively affected by intense management (Moebius et al., 2007). Reduced tillage typically improves soil physical qualities by allowing better water infiltration/movement through the soil and promoting healthy root growth, especially for soils with a high clay content (Sağlam et al., 2015).

Agricultural management decisions are born from the knowledge, understandings and beliefs of the land manager (Romig, Garlynd, Harris & Mcsweeney, 1995; Wauters, Bielders, Poesen, Govers & Mathijs, 2010; Ingram, Fry & Mathieu, 2010). Although soils possess inherent characteristics such as the texture or depth that are constrained by time, parent material, local climate, ecology, and topography, management decisions affect soil to a significant extent (Doran, 2002). Agricultural change over the past century – broadly represented by a shift from on-farm nutrient-cycling to off-farm inputs, and a shift in knowledge from the farmer to the chemical company – have negatively impacted the soil. The concept of soil health has risen out of this need to address soil issues in a more comprehensive manner.

1. Defining Soil Health

The term ‘soil health’ arose over the past two to three decades as a recognition that soils are complex systems with physical, chemical and biological components that interact with each other and with the surrounding environment. The term ‘soil health’ is often preferred by farmers and producers because it represents a holistic approach to soil management (Idowu et al., 2008). Farmers are primary land managers and play a major role in

determining soil health at the field, farm and regional level (Doran, 2002; Ingram et al., 2010; Lima, Brussaard, Totola, Hoogmoed & de Goede, 2013), however, because soil is such a complex system, the best management decisions can only be made when a high level of information is available. In this light, the soil health concept represents a unique opportunity to engage with producers and to promote more holistic soil knowledge while translating complex scientific knowledge into practical soil management strategies (Doran, 2002).

However, there is often a wide gap between farmer and scientist interpretations of soil health, meaning that farmers may make management decisions with incomplete or incorrect information, and that scientists may not understand on-farm soil needs or communicate useful soil management information in a helpful way (Romig et al., 1995; Ingram et al., 2010). To improve on-farm management decisions and direct research toward topics that are useful for farmers, scientists must understand the perceptions that farmers have about soil health (Doran et al., 1996; Savard, Mackenzie & Hammermeister, 2014). In addition, scientists must acknowledge their own limitations in understanding farm management needs, and be aware of the gaps in farmers' soil health knowledge to provide more useful soil information to farmers. Finally, robust and practical tools for assessing soil health in the Maritimes must be developed to ensure that scientists and practitioners can accurately quantify soil health and how it is affected by management decisions.

1.1. The Academic Perspective

Conceptual discussion of health as applied to soils is still in relative infancy and suffers from fragmentation and division along disciplinary lines (Doering et al., 2015). One of the most widely used academic definitions of soil health is drawn from Doran et al. (1996, p.

11): “the continued capacity of a living soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, maintain the quality of air and water environments, and promote plant, animal and human health.” This definition was further expanded by Doran (2002) to encompass not only the current condition of the soil, but also the economic and environmental sustainability of the land manager’s practices. A similar, though simpler, definition was proposed by Magdoff (2001), “the ability of soil to support and sustain crop growth while maintaining environmental quality” (p. 169). Resiliency – the soil’s ability to recover from stress – is also important for soil health (Meurisse, 1999; Congreves, Hayes, Verhallen & Van Eerd, 2015; Doering et al., 2015).

Kibblewhite, Ritz & Swift (2008) differentiate soil health definitions as being either ‘reductionist’ or ‘integrated’. Reductionist definitions incorporate a set of useful biological, physical and chemical soil indicators that are more compatible with typical soil tests (Kibblewhite et al., 2008). Broader or ‘integrated’ definitions of soil health recognize the evolutionary and emergent properties of soil, where the whole soil ecosystem is more than the sum of its parts (Kibblewhite et al., 2008). Research tends to focus on reductionist definitions because integrated soil health is more difficult to measure and therefore less useful for practical applications (Kibblewhite et al., 2008). Examples of this reductionist approach to soil health research include the work of Doran et al. (1996); Moebius-Clune et al. (2016); or Morrow, Huggins, Carpenter-Boggs & Reganold (2016). In developing indicator sets to measure soil health, parallels are often drawn between soil health and human health: certain characteristics must be met; biological, chemical and physical processes must be fully functioning; and there must be an absence of disease or parasites (Magdoff, 2001). Healthy

soils must support crop growth without undue stress to the plant or the environment (Magdoff, 2001).

Advocates for a broader definition of soil health have explored the cyclical relationship between soil health and human health, arguing that the two are tightly linked and that definitions that revolve solely around benefits to agriculture or the environment limit the concept's adaptability (Bennett, Mele, Annett & Kasel, 2010; Pepper, 2013). For example, soil health may influence human health through its ability to provide ecosystem services such as water and air quality remediation, through its regulation of disease and pathogens, and through its ability to support healthy crops (Bennett et al., 2010; Pepper, 2013).

The soil health concept differs from soil quality in that the latter generally focuses on soil productivity or suitability for a given use (Carter, 2002). As in the case of soil health, soil quality definitions range from the relatively narrow (crop productivity on a given soil) to the complex (soil ability to provide suitable microbial habitats) (Karlen et al., 1997). Although assessing soil quality requires a well-rounded assessment of functions, processes and indicators, the goal of these assessments is directed toward the ability of a soil to provide a given service or number of services, rather than its integrated landscape roles (Carter, 2002). Soil health is therefore a more holistic measure of the soil than soil quality (Doran et al., 1996).

1.2. The Farmer Perspective

Land managers are key players in determining soil health, and their perceptions of what is good, and how "good" can be achieved, are vital (Doran, 2002; Ingram et al., 2010;

Lima et al., 2013). Farmers may prefer the term soil health over soil quality because it incorporates a more holistic approach to soil processes (Idowu et al., 2008).

Studies exploring farmers' soil health perceptions typically find that farmers and scientists operate on different scales of assessment (Romig et al., 1995; Ingram et al., 2010). Farmers and scientists may make the same observations, for example by noticing erosion in a field, but use different words or different meanings (Ingram et al., 2010). Generally, farmers have a broader knowledge of the entire farm, and a working knowledge of the soil, but may not connect soil processes to the history of the land or the surrounding landscape (Ingram et al., 2010). Scientists have a deeper knowledge based on in-depth information from quantitative lab or in-situ tests and an ability to compare to the larger landscape, but often do not consider working soils or whole farm requirements (Ingram et al., 2010).

For farmers, soil measurement is inseparable from soil management, and processes – the long-term effects of management decisions – may be more important than the measures themselves (Romig et al., 1995). Farmers also possess an intuitive sense of the soil, drawn from years of experience in working the land, which lends a temporal depth to their analysis (Romig et al., 1995). Farmers are typically more reliant on sensory and qualitative judgements than scientists (Romig et al., 1995; Lobry de Bruyn & Abbey, 2003). For example, soil parameters such as organic matter, pH, fertility and erosion may take precedence, but farmers also rely on broader indications of soil health, such as plant/animal health and crop yield (Romig et al., 1995).

Insights from Fairhead & Scoones (2005) highlight the importance of recognizing social, cultural and economic contexts when assessing soils. Though soil management practices are affected by a farmer's worldview (Schneider, Ledermann, Fry & Rist, 2010), soil

research is often biased by scientific views that undervalue the role of traditional knowledge and the social, cultural and environmental history of the land (Fairhead & Scoones, 2005). Social relationships with other farmers, as well as aesthetic perceptions and deep-rooted ideologies about "what it means to be a farmer" influence how soil health is perceived and the level of control farmers feel they have over improving their own soils (Schneider et al., 2010). Communication between farmers and scientists must consider social pressures faced by farmers (Schneider et al., 2010). For example, Swiss farmers view tillage as a traditional part of being a farmer, and attempts to promote conservation tillage or no-till practices must recognize this mindset (Schneider et al., 2010). Farmers' attitudes towards a behaviour are an important determinant of whether a practice will be adopted (Wauters et al., 2010).

2. Measuring Soil Health

Practical and accurate assessment of the soil condition is an undisputed requirement for maintaining and improving soil health; which measurements these assessments should include is a more controversial question. Doran et al. (1996) advocate for the use of indicators of soil health with threshold values that change based on the soil type, ecosystem, landscape and land use in question. Typically, these indicators must represent all three areas of soil health, namely, the physical, chemical and biological components of a soil system, which may be measured in laboratory or *in-situ*.

The Cornell Comprehensive Assessment of Soil Health (CSHA), made available in 2006, is based on extensive research in the New York region to develop a minimum dataset for assessing physical, chemical and biological aspects of the soil through a series of lab tests

and in-field measurements (Schindelbeck et al., 2008; Idowu et al., 2008; Moebius-Clune et al., 2016). Based on a need for comprehensive, cost-effective, sensitive and consistent soil health testing, the CSHA assesses between 9 and 16 indicators, including SOM, soil respiration, active C, soil protein, nutrient levels, soil compaction, wet aggregate stability and available water capacity, to rate the soil's healthfulness on each indicator as well as overall.

Extensive testing in the New York region by the Cornell team has indicated that it is a robust test for the area (Schindelbeck et al., 2008; Idowu et al., 2008; Moebius-Clune et al., 2016). The CSHA rating system is based on a regional soil database collected by Cornell University, and therefore does not necessarily reflect real biological or environmental thresholds. Ongoing research is working to validate the tests for other regions, with mixed results. In Ontario, the CSHA has been found to correlate well with SOC and total N (Van Eerd, Congreves, Hayes, Verhallen & Hooker, 2014), but to be more sensitive overall when some of the individual indicators are weighted in the overall score using principal component analysis (PCA) (Congreves et al., 2015).

The Haney Test is a soil health test commercially available through several laboratories in the United States. The test includes a 24-hour incubated Solvita® test for CO_2-C, water-extraction of organic C, total N, NO_3-N, NH_4-N, and PO_4-P, and H^3A-extraction (Haney, Haney, Hossner & Arnold, 2006) of Al, Fe, P, Ca and K (Ward Laboratories, n.d.). The water-extraction was developed and evaluated by Haney et al. (2012), who found that water-extractable organic C:N was a sensitive indicator of soil microbial activity and correlated more closely with soil respiration than did SOC or total organic N (TON). The Haney Test calculates "overall soil health" using the following equation: 24 h CO_2-C / (organic C:N ratio + (water-extractable organic C/100) + (water-extractable organic N/10)).

Haney soil health scores vary from 1 to 50, with 'ideal' being above 7 and increasing over time (Ward Laboratories, n.d.). The lab also recommends specific cover crop planting mixes based on this score to improve soil health.

The Haney Test has received little attention until recently, but initial evaluation from the soil health research community is critical. The reproducibility of the test is limited, requiring improved standardization between labs and more robust calibration with field experiments (Sullivan & Granatstein, 2015). The CO_2 respiration methodology was unreliable for Californian soils (Sullivan & Granatstein, 2015), and highly variable and insensitive to management in the Pacific Northwest (Morrow et al., 2016). Ongoing work by the University of Guelph in partnership with the Grain Farmers of Ontario is evaluating the validity and applicability of the Haney Test for Ontario soils, with estimated completion in 2018 (Grain Farmers of Ontario, 2016).

Phospholipid fatty acid analysis (PLFA) is another lab-based test with potential as a soil health measure because of its strength in simultaneously assessing microbial structure and function. Unique fatty acids, or groups of fatty acids, have been linked to specific groups of microorganisms and can be differentiated based on chain length, branching and saturation (Willers, van Rensburg & Claassens, 2015). The PLFA profile can be used to characterise community composition, determine microbial biomass, and provide an indication of the metabolic or functional state of the community (Frostegård, Tunlid & Bååth, 2010).

There are only a few studies that have directly related PLFA analyses to soil health or soil quality assessment, many of which apply a limited definition of soil health. Shestak & Busse's (2005) paper represents one of the more comprehensive applications of PLFA to soil health assessment, where physical characteristics (bulk density, pore size, water-holding

capacity, gas diffusion) were related to biological indicators, including microbial biomass, respiration, N-mineralization and PLFA. More studies have compared PLFA to other biological indicators such as microbial biomass C, basal respiration, substrate induced respiration (SIR) (Zhang et al., 2014), saprotophic fungal diversity (Orr et al., 2015), and profiles of 18S rRNA (Vargas Gil et al., 2011). Other work has used PLFA to differentiate between soils that differ in management practices, without drawing a clear connection to soil health: PLFA profiles shift between organic and conventional management (Bossio, Scrow, Gunapala & Graham, 1998), and between grazed and ungrazed grasslands (Bardgett, Leemans, Cook & Hobbs, 1997). Other aspects of soil quality, including pH (Rousk, Brookes & Baath, 2010; Frostegård, Bååth & Tunlid, 1993a), SOM (Bardgett et al., 1997) and heavy metal contamination (Frostegård, Tunlid & Bååth, 1993b) also impact PLFA profiles. Given these strengths of PLFA, it would be useful to explore its relationship to more comprehensive soil health assessments.

A more novel soil health test uses the bio-indicator *Folsomia candida* (Willem), which is a species of springtail currently used internationally (ISO, 1999) for assessing soil toxicity based on its survival and fecundity when exposed to soil in a lab incubation (Environment Canada, 2014). Nelson, Boiteau, Lynch, Peters & Fillmore (2011) refined this lab-based test and demonstrated the potential effectiveness of using *F. candida* to assess soil quality in agricultural soils, based on changes in body length of one day old neonates over a period of 23 days. This species is ideal for soil health analyses because it is widely distributed globally and closely associated with many soil processes, including nutrient cycling, SOM decomposition, microbial activity and microbial biomass (Nelson et al., 2011).

Some soil health tests may also be wholly or partly conducted in-field. For example, the CSHA uses *in-situ* penetrometer readings as an indicator of soil compaction, and the CSHA rainfall simulator, which is used for measuring water-stable aggregates, can also be used in-field to assess infiltration. Earthworm counts are another robust and widely-used in-field soil health assessment (Pankhurst et al., 1995; Doran & Zeiss, 2000).

In-field soil health scorecards have also been developed as useful tools for farmers to assess soils without the need for special equipment. Romig et al. (1995) developed the Wisconsin Soil Health Scorecard after extensive interviews with Wisconsin farmers about the indicators they use to assess soil health on their farms. The full scorecard uses 43 indicators of a vast range – from chemical, physical and biological soil parameters, to animal and plant health – to develop an overall mark for the soil (Romig et al., 1995). The Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) has also developed an online soil health test that can be used by farmers, and includes indicators such as erosion, nutrient levels, pH, OM, plant vigour, water holding capacity, soil life, and soil tilth (OMAFRA, 2016).

3. Research Objectives and Hypotheses

The soil health concept is a recognition of soil's inherent complexity. Farmers' management practices play a major role in affecting soil health; these practices are affected by the farmers' perceptions and values, which may differ significantly from scientific perspectives. Because soils are complex, management decisions should be based on information about the soil, its processes and current state. However, there is no clear consensus on the definition and best methods for assessing "soil health", even within the

scientific community, and soil health perceptions may differ even more between scientists and farmers.

To improve management practices on-farm, it is important for scientists to understand the perceptions that farmers have about soil health. Scientists must also be aware of the gaps in farmers' soil health knowledge to provide more useful soil information. Finally, it is important to develop robust and practical tools for assessing soil health in the Maritimes.

Therefore, the objectives of this work are:

1. To evaluate the CSHA, the bio-indicator *Folsomia candida* test, and PLFA for assessing soil health in agricultural fields in the Maritimes (Chapter 2).

   Hypotheses:

   1. That the CSHA & *F. candida* bio-assay will show similar trends when assessing soil health, as assessed on twelve selected soils using one-way analysis of variance and Pearson's correlation.
   2. That shifts in PLFA profiles can be associated with changes in CSHA indicators through multivariate analysis.
   3. That these soil changes will be linked with field management history (rotation, tillage regime, and application of manure, compost, lime fertilizers, herbicides, pesticides, fungicides) as well as environmental factors.

2. To characterize farmers' perceptions of soil health and understand how farmers assess their own soils (Chapter 3).

   Hypotheses:

1. That farmers' soil health perceptions will reflect their needs and interests on the farm, and will therefore be more management/production focused than literature definitions of soil health.
2. That farmers' soil health perceptions will differ between farm types and farmer demographics, as determined through structured interviews.

3. To compare farmers' in-field soil health assessments to a laboratory-based soil health assessment (the CSHA) (Chapter 3).

Hypotheses:

1. That the farmer's in-field soil health scorecard and the CSHA will consistently distinguish between 'good' and 'poor' soils on each farm.
2. That farmers will agree with CSHA results for soil characteristics that they are familiar with, such as nutrients levels, and will disagree with CSHA assessments of unfamiliar or novel soil characteristics, based on the ranking of seven parameters common to the in-field scorecard and the CSHA.

Chapter 2: Comparison of Three Soil Health Assessments and their Responses to Management History and Environmental Factors

1. Introduction

Although healthy soils promote the provision of ecological services, soil degradation can lead to environmental strain and loss of productivity (Bennett et al., 2010; Pepper, 2013). Research in recent decades has pursued the idea of "soil health", though researchers have failed to reach a consensus on one clear definition of the term (Kibblewhite et al., 2008). Broadly, soil health is understood to be the combination of physical, chemical and biological properties that promote the ability of a soil to support human, plant and animal needs while maintaining or enhancing environmental quality (Doran et al., 1996; Moebius-Clune et al., 2016).

Assessing soil health requires more comprehensive testing than conventional soil quality work that focuses on a few individual parameters (Karlen et al., 1997). Soil health assessments must not only encompass chemical, biological and physical indicators, but should ideally also assess trends and emergent properties (Karlen et al., 1997). Methods for assessing soil health range from in-field observational scorecards, such as the Wisconsin Soil Health Scorecard (Romig et al., 1995) to comprehensive laboratory tests of a minimum set of indicators, such as Cornell's CSHA (Moebius-Clune et al., 2016) or the Ontario Soil Health Assessment (OSHA) (Congreves et al., 2015). Both methods assess specific indicators that represent the chemical, physical and biological aspects of the soil.

Other soil health work has explored bio-indicator species of soil health, such as presence or abundance of nematodes, earthworms, collembola, or abundance and diversity of

microbial indicators (Pankhurst et al., 1995; van Bruggen & Semenov, 2000; Griffiths et al., 2016). Recent work in Europe has suggested that many biological indicators differentiate between site-level differences, though most are not sensitive enough to management practices on their own and should therefore be integrated with a suite of other indicators (Griffiths et al., 2016). *Folsomia candida* (Willem) springtails show potential as a soil health indicator (Kaneda & Kaneko, 2002; Nelson et al., 2011); phospholipid fatty acid (PLFA) profiles of soil microbial groups is another possibility (Bossio et al., 1998; Shestak & Busse, 2005; Zhang et al., 2014).

1.1. Measuring Soil Health

1.1.2. The Cornell Soil Health Assessment

The CSHA was made available in 2006 as a cost-effective protocol for assessing soil health in the New York region. It incorporates key physical, chemical and biological indicators chosen for their relevance, sensitivity, consistency and cost, and has been evaluated in multiple trials (Schindelbeck et al., 2008; Idowu et al., 2008; Moebius-Clune et al., 2016). Depending on the tests selected, between 9 and 16 indicators are assessed; in the standard package, these indicators include soil texture, available water capacity (AWC), surface and subsurface hardness, wet aggregate stability (WSA), organic matter (OM), Autoclaved-Citrate Extractable (ACE) soil protein, soil respiration, active C, and standard nutrient analysis. There are four additional add-on tests: potentially mineralizable-N (PMN), root pathogen pressure, heavy metal contamination, and soil salinity and sodicity.

Each indicator is scored out of 100 and given a colour (red, yellow or green) based on its interpretation as low, medium or high. The soil is also given an overall mark, although each indicator's score should be assessed individually (Moebius-Clune et al., 2016). Scores are calculated within soil textural classes for each indicator based on Cornell's soil database. Thus, the scoring does not represent real biological or physical thresholds but is a comparison to a regional range of parameters, which is a challenge for using the test in other regions. In addition, the scoring system is not calibrated to yield data, which may limit the usefulness of the test from a farmer's perspective.

Recent work has attempted to validate the CSHA for use in other regions. Van Eerd et al. (2014) used the CSHA along with SOC and total N to assess soil health differences between tillage management types in long-term (20 year) field trials in southwestern Ontario. The CSHA's assessment of soil health matched the assessments of SOC and total N (Van Eerd et al., 2014). Congreves et al. (2015) compared soils from field trials of no-till, diverse rotational systems to conventionally tilled monocultures in Ontario. The authors used the CSHA as well as an Ontario Soil Health Assessment (OSHA), which assessed the same indicators as the CSHA but used weighted averages based on principal component analysis (PCA) (Congreves et al., 2015). PCA showed that root health, sand content, Mn, and pH were less valuable as soil health indicators in Ontario, and using weighted averages made the OSHA more sensitive to management effects (Congreves et al., 2015).

Given these potential improvements on the CSHA and the fact that CSHA scoring is based on regional New York data, it is important to evaluate the CSHA for Maritimes soils. There is ongoing work in PEI and NS to explore the robustness and sensitivity of the CSHA in the Maritimes; this project is partially linked with that work.

1.1.2. F. candida Bio-Assay

Collembolans have previously been recommended for use as bio-indicators of soil quality in agricultural systems and are known to be sensitive to tillage and N-fertilization (Pankhurst et al., 1995; van Bruggen & Semenov, 2000). Their lifecycle is linked to a variety of soil processes, including SOM decomposition and nutrient cycling, and collembolans form complex relationships with soil microbes through their feeding activities (Fountain & Hopkin, 2005; Bitzer, Rice, Pilcher, Pilcher & Lam, 2005; Nelson et al., 2011). The collembolan species *F. candida* has become a standard for eco-toxicology and pollutant testing in worldwide soils over the last 40-50 years (ISO, 1999; Fountain & Hopkin, 2005). Environment Canada's biological test methods for soil contaminants assess survival and reproduction of *F. candida* during exposure to soil samples (Environment Canada, 2014). Initial work has also demonstrated the potential effectiveness of *F. candida* bio-assays to indicate soil quality in forest soils (Kaneda & Kaneko, 2002) as well as agricultural soils based on changes in body length of one-day-old neonates (Nelson et al., 2011). To date, the latter bio-assay test has not been compared with an integrated test such as the CSHA to assess soil health, nor has it been used to assess agricultural soils across a wide variety of sites and management strategies.

1.1.3. Phospholipid Fatty Acid Analysis

Phospholipid fatty acids are present in all living cells and are found in the cell membranes of microorganisms (Hill et al., 2000). Unique fatty acids, or groups of fatty acids, have been linked to specific groups of microorganisms and can be differentiated based on chain length, branching and saturation (Willers et al., 2015). Biomarker patterns or individual

biomarkers can be used to identify microbial groups, such as arbuscular mycorrhizal fungi (AMF) or Gram-negative bacteria (Willers et al., 2015).

PLFA profiles are detailed enough to demonstrate differences in the microbial community affected by management practices and soil factors. Bossio et al. (1998) found significant differences between PLFA profiles in organic and conventional field plots, and Bardgett et al. (1997) found a clear shift in microbial community as grasslands shifted between grazed and ungrazed management. The effect of pH on PLFA profiles is also marked: PLFA profiles are sensitive to pH both in agricultural soils (Rousk et al., 2010) and in forest soils exposed to lime (Frostegård et al., 1993a). Compaction has a smaller effect on PLFA profiles (Shestak & Busse, 2005). PLFA is useful for measuring fungal:bacterial biomass ratios (Frostegård & Bååth, 1996; Bardgett, Hobbs & Frostegård, 1996; Baath & Anderson, 2003), where a higher fungal:bacterial biomass ratio is linked to increased C storage potential in soils (Malik et al., 2016). Given the limited work dedicated to relating PLFA to more comprehensive soil health measures, it would be useful to compare PLFA profiles to the CSHA.

2. Objective and Hypotheses

This chapter is focused on Objective 1: to evaluate the CSHA, the bio-indicator *Folsomia candida* test, and PLFA for assessing soil health in agricultural fields in the Maritimes. It was hypothesised that: 1) the CSHA & *F. candida* bio-assay will show similar trends when assessing soil health, as assessed on twelve selected soils using one-way analysis of variance and Pearson's correlation; 2) shifts in PLFA profiles can be associated with

changes in CSHA indicators through multivariate analysis; and 3) these soil changes will be linked with field management history (rotation, tillage regime, and application of manure, compost, lime, fertilizers, herbicides, pesticides, fungicides) as well as environmental factors.

3. Methods

3.1. Site Selection and Soil Sampling

A suite of farms of various types and locations across Nova Scotia, New Brunswick and Prince Edward Island were selected to participate in this study. Farmer participation was initiated through an online survey circulated to farmers through Maritimes agricultural organisations, namely: Perennia, the Atlantic Canadian Organic Regional Network (ACORN), PEI Certified Organic Producers Co-Operative (PEICOPC), PEI Department of Agriculture and Fisheries, Soil and Crop Improvement Nova Scotia, Farmers Markets Nova Scotia, Horticulture Nova Scotia, Dairy Farmers of Nova Scotia (DFNS) and Milk 2020. Fifty-nine farmers participated in the survey by the deadline on July 31, 2016, including 14 PEI farms, 15 New Brunswick farms and 29 Nova Scotia farms. Farmers responded to the question "How do you know what is a healthy soil and what is a bad soil?", and those interested in participating in interviews and soil sampling provided their contact information, as well as basic demographic information about their farm to enable farm selection. Farms were selected in consultation with committee members, endeavouring to include a wide variety of farm types, intensity of management practices, and locations throughout the Maritimes.

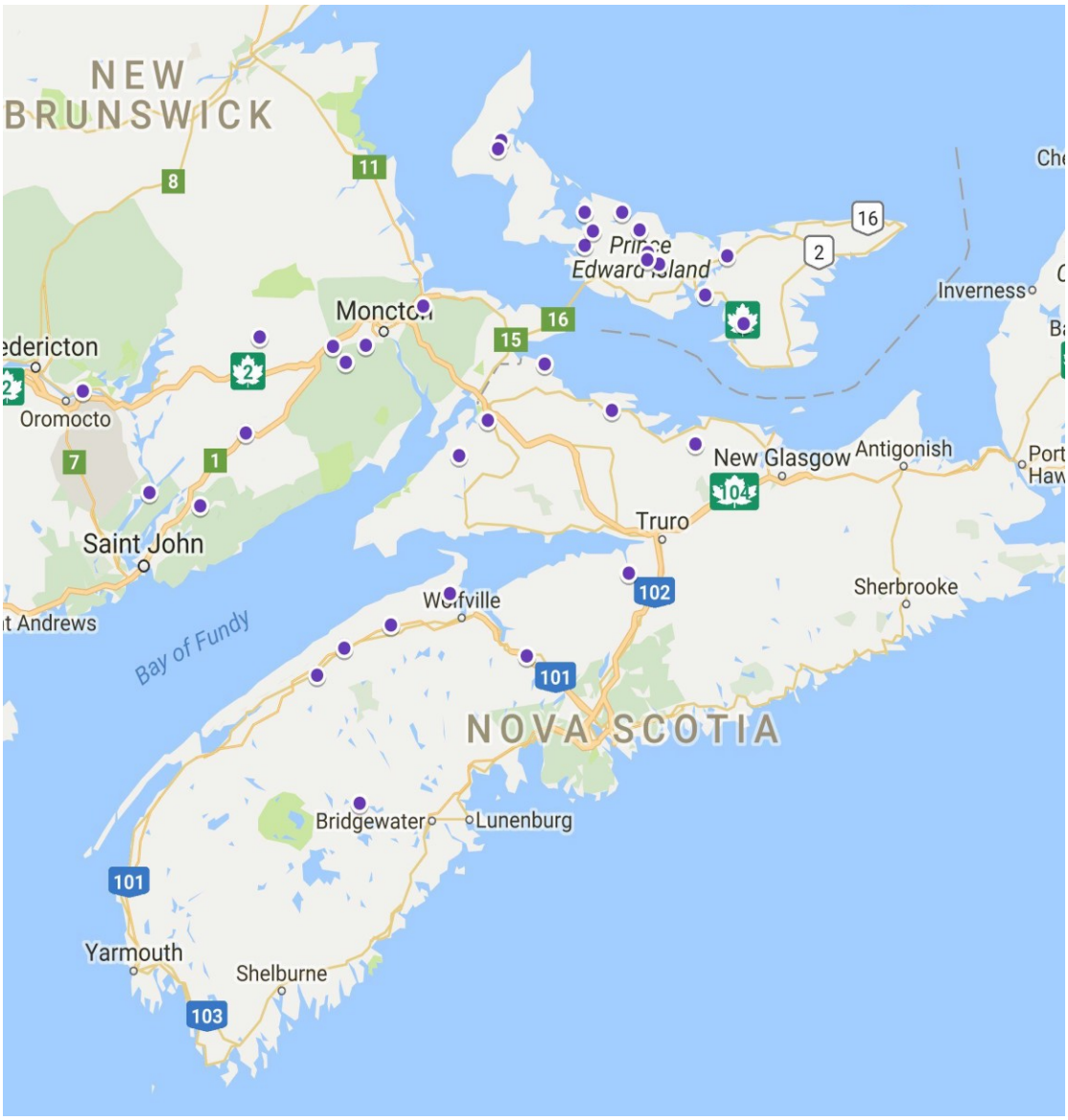


Figure 1. Blue markers showing the 34 farms visited across the Maritimes: NB (9), NS (12) and PEI (13).

Thirty-four farms were visited between August 11 – September 16, 2016: nine farms in New Brunswick, 12 farms in Nova Scotia, and 13 farms in PEI (Figure 1). Farm types varied widely: 14 farms were organic and 20 conventional, including 17 vegetable, eight dairy, six field crops, and three beef/sheep farms (Table 1). Although farm-size information

was not collected, it was clear that farms varied in size from very small (less than an acre under production) to very large (hundreds of acres).

Table 1. Participant farms by province and farm type.

	New Brunswick		Nova Scotia		Prince Edward Island		Total
	Organic	Conv.	Organic	Conv.	Organic	Conv.	
Vegetable	2		5	3	4	3	17
Dairy		6		1		1	8
Field crops		1			2	3	6
Beef/Sheep			1	2			3
Total	2	7	6	6	6	7	34

Farmers were asked to select a "good" and a "poor" soil on their farm, based on their own perceptions, and farmers filled in a soil health scorecard for each of the two fields on their farm. In addition to an interview, farmers provided basic background information about themselves and about the farm, including field history and management intensity (current crop and 5-year crop history; type and frequency of tillage; type, frequency and amount of inputs used: manure, compost, fertilizers, herbicides, pesticides, fungicides), as well as farmer demographics (age, sex, farming experience, education, and soil science training, e.g. classes/workshops.)

Soil samples were collected from both "good" and "poor" fields in accordance with the methods suggested in the Comprehensive Assessment of Soil Health Manual for the CSHA (Moebius-Clune et al., 2016). Samples were collected at 10-15 points per field, depending on field size. The field was sampled in a "W" pattern to ensure that the entire field was covered. At each point, surface debris was removed, and a core was collected 5 cm in diameter and 15 cm deep using a shovel. Care was taken to ensure that all cores were a standard depth and diameter by marking the shovel to indicate the required core size and following that guideline at each sampling point. Penetrometer readings were taken and

maximum hardness recorded for the depths 0-15 cm and 15-46 cm (surface and subsurface hardness, respectively). Samples were mixed thoroughly in a bucket, and 2-3 kg of soil were bagged and placed in a cooler with ice.

3.2. Sample Processing

Immediately upon return to the lab, approximately 50 g of soil was separated and stored at -20° C for PLFA analysis. The bulk of the soil was stored at 4° C until further processing. At the end of the sampling period, approximately 1 kg of soil was sieved (8 mm) and set out to air-dry to constant weight. The remainder of the soil was returned to the cooler for the *F. candida* bio-assay. From the air-dried sieved soil, ~250 g was subsampled for chemical analyses, and 100 g was bagged for soil respiration analysis and the Autoclave-Citrate Extractable (ACE) Protein Test. The remainder of the air-dried soil was sieved (2 mm) and divided for the following tests: active C and AWC (approximately 200 g) and textural analysis and soil moisture content (100-150 g). In addition, approximately 80 g of 2 mm-0.25 mm soil aggregates were separated using a W.S. Tyler Ro-Tap® Coarse Sieve Shaker for WSA testing.

3.3. CSHA Analyses

Analyses for the CSHA were conducted as closely as possible to the operating procedures outlined in Cornell's Standard Operating Procedures published in February, 2016 (Cornell Soil Health Laboratory, 2016). Any procedural differences are noted below.

3.3.1. Soil Nutrients, pH and Organic Matter

Nutrient analysis, pH and OM were conducted by the PEI Analytical Laboratory in Charlottetown, PEI. The PEI laboratory measures OM as C on a combustion analyzer and converts this to OM. Nutrient analyses are conducted using Mehlich-3 extractions rather than Morgan extractions, which Cornell uses.

3.3.2. Soil Texture

Soil texture was determined using the Buoycous Hydrometer method (Sheldrick & Wang, 1993) rather than the CSHA rapid soil texture method (Cornell Soil Health Laboratory, 2016). Soil was soaked overnight in a beaker with 100 mL of Calgon® solution and approximately 300 mL of distilled water; 100.0 g of soil was used for the sandier soils in PEI and 50.0 g of soil was used for the Nova Scotia and New Brunswick soils with a lower sand content. The following morning, this mixture was mixed using a magnetic stirbar for 5 minutes, transferred to a cylinder and the volume brought to 1 L with distilled water. The contents were mixed thoroughly using a plunger before hydrometer readings were taken at 40 seconds (R40) and 7 hours (R7h). The null density of the Calgon® solution was measured at room temperature (RL). 20.0 g of soil was oven-dried at 105° C for 24 hours and weighed to determine moisture content. Texture was calculated using the following formulas:

Sand % = 100 - (R40s - RL) * (100/oven-dry soil weight)

Clay % = (R7h – RL) * (100/oven-dry soil weight)

Silt % = 100 - (clay % + sand %)

3.3.3. Active Carbon

A solution of 0.2 M $KMnO_4$ was prepared in advance by mixing 11.09 g $CaCl_2$ with 750 mL distilled water, adding 31.61 g $KMnO_4$ and bringing the volume to 1000 mL (pH adjusted to 7.2). Air-dried soils were measured out in 2.50 g duplicates. In sequence, the soil was added to a shaker bottle containing 18 mL distilled water, and 2 mL of 0.2 M $KMnO_4$ was added to begin the redox reaction. The bottles were shaken at 180 rpm for 2 minutes, and then left to stand on the bench to continue the reaction for a further 8 minutes. After a total reaction time of 10 minutes, a 0.5 mL aliquot was removed, stopping the reaction, and added to a tube containing 49.5 mL distilled water. This tube was shaken by hand for ten seconds, and then absorbance was read on a spectrophotometer at 550 nm. Duplicates which differed in absorbance by greater than 5% were re-run.

Loss of colour in the $KMnO_4$ solution is proportional to oxidization of active C: as 0.75 mol or 9000 mg of C oxidizes, it consumes 1 mol of MnO_4 by reducing Mn^{7+} to Mn^{2+} (Cornell Soil Health Laboratory, 2016). To calculate mg active C/kg soil, a standard curve was developed by measuring absorbance in triplicate samples of known $KMnO_4$ concentrations (0.005 M, 0.01 M and 0.02 M) and graphed with concentration as the y-variable and absorbance as the x-variable. Calculations were then completed using the following formula:

Active C (mg/kg) = [0.02 mol/L - (a + b * absorbance)] * (9000 mg C/mol) * (0.02 L solution/0.0025 kg soil)

where

0.02 mol/L is the solution concentration

a=y-intercept of standard curve

b=slope of standard curve

9000 mg C/mol is the C oxidized by 1mol of MnO_4 changing from Mn^{7+} to Mn^{2+}

0.02L is the volume of $KMnO_4$ solution

0.0025kg is the amount of air-dry soil

3.3.4. Wet Aggregate Stability

Soil aggregates were separated using a W.S. Tyler Ro-Tap® Coarse Sieve Shaker with nested 2 mm and 0.25 mm sieves. The sieves were shaken for 15 seconds and the 2 mm-0.25 mm aggregates were collected into capped glass tubes and stored for about two months until analysis.

Two tablespoons (~ 20 g) of aggregates were spread onto a pre-weighed 0.25 mm sieve, which was weighed again and placed over a filter in a funnel. The sieve was then placed under the rainfall simulator, which was calibrated so that 1.25 cm of water depth fell over a period of 4-6 minutes from a height of 50 cm, generating a total kinetic energy of 1.9 Joules. This is a slight variation from Cornell methods, which suggest 1.25 cm over a 5-minute period; the change was made because the rainfall simulator was found to vary slightly between runs. When the sieve was placed under the rainfall and the timer was started, the water level was noted and the sieve was removed once the level dropped by 1.25 cm, as long as the time was within 4-6 minutes. The “failed” soil that had fallen through the sieve was captured on the filter, which was rolled and placed in an aluminum can (“filter can”). The soil remaining on the sieve surface was washed through the sieve and any sand or stones that could not fit through the sieve was collected into a can (“sand can”). The sand can and the filter can were oven-dried at 105° C for 24 h and weighed.

Percent WSA was calculated using the following formula:

(((initial soil on sieve (g) – sieve wt (g)*air-dry moisture content)) – (dry rock and sand can (g) – can wt (g)) – (dry filter and failed soil (g) – filter wt (g) – can wt (g))) / ((initial soil on sieve (g) – sieve wt (g)) – (dry rock and sand can (g) – can wt (g))) * 100

3.3.5. Soil Respiration

Air-dry, 8 mm-sieved soil was weighed out in 20.00 g duplicates into aluminum tins with 9 punctured pinholes in the bottom. Aluminum tins were placed into 500 mL jars with 2 filter papers in the bottom to facilitate capillary draw of water into soil samples. A scintillation vial attached to a small "pizza stool" was placed into the jar so that it sat above the soil. Fresh 0.5 M KOH was drawn into a small beaker, over which was placed an upturned beaker to limit CO_2 absorbance from the atmosphere. In sequence, 9 mL of KOH was carefully pipetted into the scintillation vials, placing lids back on the jars after the KOH was added. Then, 7.5 mL of distilled deionized water was carefully pipetted down the side of the jar to be taken up by the soil through capillary action. The sequence was completed for a set of 12 jars at once (11 samples plus one blank). The jars were then allowed to sit for four days at room temperature. After incubation, electrical conductivity (EC) of the KOH was measured in sequence.

Calculation of CO_2 respiration assumes that one mole of KOH can absorb 0.5 mole of CO_2 and, when fully saturated, 0.5 M KOH can take up enough CO_2 to become 0.25 M K_2CO_3. 9 mL of 0.5 M KOH can absorb 99.025 mg CO_2 (Cornell Soil Health Laboratory, 2016). Electrical conductivity was measured in a 0.25 M K_2CO_3 solution to represent a "saturated" trap, and in the raw (blank) 0.5 M KOH to represent the 'nil' value. CO_2 absorbed during the 4-day incubation can therefore be represented as the proportion of the trap capacity CO_2 that was absorbed:

$$P=((EC_{raw} - EC_{sample})/(EC_{raw} – EC_{sat}))$$

Where

P = proportion of trap capacity CO_2 absorbed

EC_{raw} = electrical conductivity of raw 0.5 M KOH

EC_{sample} = electrical conductivity of the sample

EC_{sat} = electrical conductivity of 0.25 M K_2CO_3

The amount of CO_2 absorbed was then calculated by multiplying P (proportion) by the trap capacity (99.025 mg CO_2).

3.3.6. Autoclave-Citrate Extractable (ACE) Protein Test

Duplicate 3.00 g air-dried soil samples were weighed into glass extraction tubes, to which 24.00 mL of the extractant sodium citrate (20 mM, pH 7.0) was added in sequence. The slurry was shaken to encourage soil dispersal for 5 minutes at 180 rpm, after which the samples were autoclaved for 30 minutes to further encourage solubilisation of proteins (total time in autoclave was 2 hours, including pressurization, heating and cooling cycles). Samples were left to cool to room temperature, after which 2 mL aliquots of the mixture were transferred to clean microcentrifuge tubes and centrifuged for 3 minutes at 10 000 x g to clarify the extract. 1 mL of cleared liquid extract was pipetted into small tubes and refrigerated overnight before quantification.

Quantification of the protein concentration in the liquid extract was determined using a microplate reader (Biotek™ PowerWave XS2) with 96-well plates. 10 µl of extract was transferred per well, with two wells allocated per duplicate (4 wells total, per sample). The

samples were run against bovine serum albumin (BSA) standards at concentrations of 0, 125, 250, 500, 750, 1000, 1500 and 2000 µg/mL. Each standard was pipetted at 10 µl/well and measured in triplicate. 200 µl of BCA working reagent, mixed according to package directions at a ratio of 50:1 of reagent A:reagent B, was slowly pipetted into each well of the plate (standards and samples) to facilitate mixing of the liquids. The microplate was then sealed with a tape seal, placed on a heat block and heated for 60 minutes at 61.5° C. After heating, the plate was allowed to cool for 10 minutes and was then gently inverted to re-incorporate condensation that had formed during heating. The plate was read on the microplate reader at 562 nm. Three samples had high protein concentrations that made the liquid too dark to read; in these cases, the samples were re-pipetted at half-volume (5 µl instead of 10 µl) and the protein content was doubled during calculations.

To calculate protein content, a standard curve was developed for the parabolic second order regression line of best fit, and protein concentration was calculated using the quadratic formula. Protein concentration (µg/mL) was then multiplied by the amount of extractant used (24 mL) and divided by the grams of soil used (3 g) to calculate protein content (µg/g soil).

3.3.7. Available Water Capacity

Available water capacity (AWC) is measured by calculating the difference in water content between soils at field capacity and at permanent wilting point. Field capacity was determined by placing saturated soil samples into a pressure plate at 0.1 bar of pressure, and permanent wilting point at 15 bar of pressure.

To determine field capacity, ceramic plates were saturated 24 hours in advance, and disturbed soil samples were poured into rings on the surface of the plate so that the rings were

filled with soil. The soil was gently flattened and compacted, and the soil was saturated with water for several hours until fully saturated. Ceramic plates were placed in the pressure plate (5 Bar Pressure Plate Extractor Cat. #1600, Soil Moisture Equipment Co.) and the pressure was slowly lifted to 0.1 bar. The samples were left until equilibrium was reached (no more water dripped out), and then weighed immediately. The samples were then transferred to an aluminum can, oven-dried at 105° C for 24 h and weighed again. A similar procedure was followed for determining permanent wilting point, however, due to equipment failure samples NB01-NS07 were run on a cellulose membrane extractor (Pressure Membrane Extractor Cat. #1000, Soil Moisture Equipment Co.) and samples NS08-PE13 were run on a new pressure plate extractor with ceramic plates (15 Bar Ceramic Plate Extractor Model #1500F2, Soil Moisture Equipment Co.). The 15 bar samples were left until the water content equilibrated, which usually took longer than the 0.1 bar samples (about 5 days).

AWC was then calculated with the following equations:

Theta M = ((weight wet soil + can) – (weight dry soil + can))/((weight dry soil + can) – weight of can)

And

AWCsample = Theta M 0.1 bar – Theta M 15 bar

3.3.8. Surface, sub-surface hardness interpretation

Penetrometer readings were taken at each sampling point in the field, and the maximum hardness was recorded between depths of 0-15 cm and 15-46 cm. These values were averaged for each field.

3.4. *Folsomia candida* Bio-Assay

The methods described in and improved upon by Nelson et al. (2011) were used, where springtail growth is directly related to soil health. Twelve soils were selected from the group to represent a range of CSHA scores. In addition, selections were made in an attempt to get a representation of different OM-level independent of CSHA (i.e., a high CSHA score with low SOM, and vice versa), although this was not always possible.

3.4.1. Substrate preparation

Soil samples were sieved to 2 mm and stored at 4 ˚C until being air-dried for use. The soil was re-wetted using deionized water corresponding to 60% water-holding capacity and mixed thoroughly by hand. Soils were left to equilibrate for 3 days at room temperature. After equilibration, 8 g of substrate was weighed into glass scintillation vials and lightly compacted by tapping the vial on the table, to maintain aggregates for *F. candida* burrowing. Moisture content was verified at the beginning and end of the trial by weight difference before and after drying at 105 ˚C for 24 h.

A quartz sand substrate (particles 0.05-0.2 mm) was used as a control. Sand was sterilized in an autoclave five days prior to experiment initiation and left to equilibrate. Two controls were used: plain sand as a ‘poor’ control, and sand with yeast added ad-lib as an ‘ideal’ control.

3.4.2. Age synchronization and test-initiation

Age-synchronized insects were selected by isolating eggs using a moistened fine-tip paintbrush and allowing the eggs to hatch for 24 hours. Unhatched eggs were discarded, and

the day-old neonates were photographed using a Leica M80 microscope and Leica DFC 295 microscope camera with LAS V3.7 software at 10X magnification. A sub-sample of 16 day-old neonates were photographed at the beginning of the experiment and length was averaged. Body length was measured from the posterior end of the abdominal segment to the anterior margin of the head between the antennae. Neonates were then randomly transferred to test vials containing the soils, with 10 replicates per soil sample. Although Nelson et al. (2011) measured growth as well as fecundity, their results indicate that growth can be used alone as a reliable predictor, as used here.

Test vials were then placed randomly into a Z-Lab Tech LHT-21030 Germinator Chamber at 20 ˚ C +/- 0.5 ˚ C, at 600 lux with a light:dark cycle of 16:8 hours. Containers were aerated weekly and a drop of deionized water was added if soils were dry. Yeast was added ad-lib to the sand with yeast control group.

3.4.3. Ending the experiment

Test vials were destructively sampled by filling individual test vials with distilled water and stirring with a glass rod to create a supernatant, which was then poured into a larger beaker. Because of their hydrophobicity, springtail floated to the surface where they were scooped out with a spoon and transferred to a small dish with 9:4 plaster of Paris:activated carbon. The higher proportion of activated carbon facilitates clearer images. The dishes were kept in the freezer beforehand to slow movement of the springtails for photographing. Each springtail was photographed separately, and then preserved in 70% ethyl alcohol.

3.5. Phospholipid Fatty Acid Analysis

PLFA analysis was conducted by the AAFC team at the Charlottetown Research and Development Centre in PEI. The process is comprised of three main steps: extraction, solid-phase extraction (SPE), methylation and analysis on a GC. Samples were stored at -20 ° C for 4 months prior to analysis.

3.5.1. Extraction

A citrate buffer was made using Solution A (3.152 g citric acid + 100 mL deionized water) and adjusting the pH to 4.0 with Solution B (4.412 g trisodium citrate + 100 mL deionized water). A saturated NaCl solution was made by mixing 250 g of NaCl with 750 mL deionized water over high heat until all crystals were dissolved. Two solutions of 1:1 Dichloromethane (DCM):Methanol and 1:2 DCM:Methanol were made by mixing 500 mL of DCM with 500 mL of MeOH, and 325 mL of DCM with 650 mL of MeOH respectively.

Soil moisture content was measured and the citrate buffer was added at 2 mL per 2-4 g of dry soil into 50 mL Teflon tubes. 7.5 mL of 1:2 DCM:MeOH was added to each tube, covered and shaken for 2 hours at 200 rpm. 10 mL of saturated NaCl solution was then added to each tube and shaken for a further 5 minutes. These were then centrifuged for 10 minutes at 3000 RPM.

After centrifugation, the middle layer between the soil and the aqueous layer was carefully removed using a pipette and place in a new glass culture vial. 5 mL of 1:1 DCM:MeOH was added to the Teflon tube to wash the aqueous phase, vortexed briefly, shaken for 15 minutes, centrifuged, and again the middle layer was removed and added to the

glass culture vial containing the previously removed layer. This solution was then dried N_2, and dissolved in DCM, which was stored at -20 °C.

3.5.2. SPE

SPE was then used to separate and purify the samples using a SUPELCO Visiprep DL. The columns were conditioned using DCM and samples were loaded. Approximately 1.5 mL of DCM was added to each column as a wash, and ~ 3 mL of acetone was added to the columns and allowed to run through completely. Approximately 1.5 mL of MeOH was added to the columns and was caught in new glass culture vials. The glass vials were then dried under N_2, dissolved in ~ 0.75 mL of MeOH and stored at -20 ° C until methylation the following day.

3.5.3. Methylation and analysis

For methylation, the fraction from the SPE step was dried under N_2 and dissolved in 1 mL of 1:1 MeOH:Toluene. 1 mL of 0.2M Methanolic KOH was added to each tube, followed by 10 µL of a 0.1 µg/µL C19:0 methyl Ester Standard to each vial. Vials were covered and incubated at 80°C for 30 minutes on a heat block, then allowed to cool to room temperature. Two mL of deionized water was added to each vial, followed by 0.3 mL of 1 M acetic acid and 2 mL of hexane. This was vortexed for roughly 30 seconds until sample turned clear, and the upper hexane layer was carefully removed and placed in a new glass culture vial. To the original tube was again added 2 mL of hexane, vortexed for 30 seconds, and again the upper layer was removed and added to the new culture vial. The fraction was taken to dryness under N_2 and the dry fraction was dissolved in 150 µL of hexane and transferred to a 2 mL GC vial.

Samples were read on a Hewlett Packard HP6890 series gas chromatograph (Agilent) using Sherlock microbial identification system (MIDI) version 6.3 to compare to a documented library of PLFAs. The GC was calibrated using the calibration standard MIDI No. 1208 for PLFAD1.

3.6. Statistical Analysis

3.6.1. Analysis for Hypothesis 1.1: F. candida bio-assay

Twelve soils were selected for the experiment to represent a wide range of CSHA scores. Collembolan growth in the different substrates over the incubation period was tested using one-way Analysis of Variance (ANOVA) and Tukey multiple means comparison. Pearson's correlation was tested between growth and CSHA indicators and scores.

3.6.1. Analysis for Hypotheses 1.2 and 1.3: CSHA, PLFA and field management

Field history data provided by the farmers were used to generate correlations between soil factors and management practices. Management factors were categorised based on the three-year field history, although information was collected five-years back, because the data for more recent years had fewer missing values. Categorisation was based on the most common management practice over the past three years, for example, a vegetable ("veg") rotation was considered any rotation that was majority vegetable crops, whereas a field that had a rotation of hay/hay/vegetable would be considered "mix" (Table 2). Raw field management information is in Appendix C.

Table 2. Description of factors and categories for field history data.

Factor	Categories	Meaning
g_p	g	Farmer-identified "good" field
	p	Farmer-identified "poor" field
rotation	grass	Three years of perennial grass (hay, grass, native grass, triple mix, grass forage, pasture)
	grain	Three years of majority annual grain (corn, wheat, oat, barley, soybean, canola, potato)
	veg	Three years of majority vegetables
	mix	Three years of a combination of annual (veg/grain) and perennial crops
	weeds	Three years of fallow and/or weeds
tillage	1	No-till
	2	Medium intensity/conservation till (conservation till, broadfork/hand till, s-tine, harrow, chisel plow, spading machine)
	3	High intensity (land-forming, sub-soiling, raised bed maker, conventional till, potato till, moldboard, 3-furrow, disc, plow, till, rototill, etc)
manure	1, 2, 3	Number of years in which solid manure (cow, horse and/or chicken) was applied over the past 3 years.
compost	1, 2, 3	Number of years in which compost (including mussel shells, biowaste, irish moss) was applied over the past 3 years.
lime	1, 2, 3	Number of years in which lime was applied over the past 3 years.
syn_fert	1, 2, 3	Number of years in which synthetic fertilizers (N, P, K, S) was applied over the past 3 years.
herb	1, 2, 3	Number of years in which any herbicide was applied over the past 3 years.
insect	1, 2, 3	Number of years in which any insecticide was applied over the past 3 years.
fung	1, 2, 3	Number of years in which any fungicide was applied over the past 3 years.

Principle component analysis (PCA) was used for data analysis because unconstrained multivariate analysis was found to explain more of the variability in the dataset than constrained analyses such as redundancy analysis (RDA) or canonical correspondence analysis (CCA). First, PCA was used as a data reduction technique on the three main data sources: soil chemical data from the PEI laboratory ("Chem"), CSHA data ("CSH") and

PLFA data ("PLFA"). The principle components of these three PCAs (PCA Scores 1 and 2 for each) were then used in a subsequent PCA to explore their relationship to the field management history and correlations with each other. Score 1 from PFLA and CSH along with Score 2 of Chem were correlated and accounted for 46% of the variation; these scores were then used in a final PCA using the original variates.

4. Results

4.1. Soil Test Results

The soils ranged widely and included Regosols, Brunisols, Podzols, Luvisols and Gleysols. All samples were coarse- or medium-textured, with average sand, silt and clay content at 53.6%, 39.1% and 7.3% respectively (Table 3). Because of drought during the sampling period, penetrometer measurements were very high for both surface and subsurface hardness at most farms. The soils ranged widely and were ranked by the CSHA between 31 and 77 – no soils scored 'Very High' (80 or above) (Figure 2). The highest-scoring CSHA indicators on average were potassium and AWC, and the lowest-scoring indicators were phosphorus and surface hardness (both ranked too high). No field scored higher than 56 for micronutrients because of high levels of iron in the soil. PLFA results showed that the biomass and ratios of various microbial groups varied widely, but that gram-negative bacteria were generally dominant (Figure 3 and Table 4). Additional results from the PEI Analytical Laboratory are in Appendix A.

Table 3. Summary statistics for 68 sampled soils.

	'Good' fields		'Poor' fields	
	Mean	SE Mean	Mean	SE Mean
Sand (%)	52.6	2.53	54.6	2.60
Silt (%)	40.3	2.33	51.1	11.09
Clay (%)	7.1	0.52	7.4	0.56
Surface hardness (PSI)	223	11.00	247	9.15
Subsurface hardness (PSI)	296	2.40	298	1.06
Available water capacity (g/g)	0.21	2.40	0.22	0.01
Water-stable aggregates (%)	61	3.88	61	4.08
Active carbon (mg/kg)	583.42	32.45	535.41	34.08
Organic matter (%)	4.2	0.31	4.3	0.54
ACE Soil Protein Index (mg/g)	10.45	0.72	8.93	2.97
Respiration (mg/g)	0.91	0.07	0.89	0.07
Phosphorus (ppm) *	142	15.73	111	15.30
Potassium (ppm)	114	10.16	101	12.04
Ph *	6.3	0.10	5.9	0.09
Magnesium	188	15.22	159	24.17
Iron	238	15.07	239	16.33
Manganese *	69	5.91	56	5.19
Zinc	4	0.59	3	0.75

* significant difference between good and poor soils at p=0.05

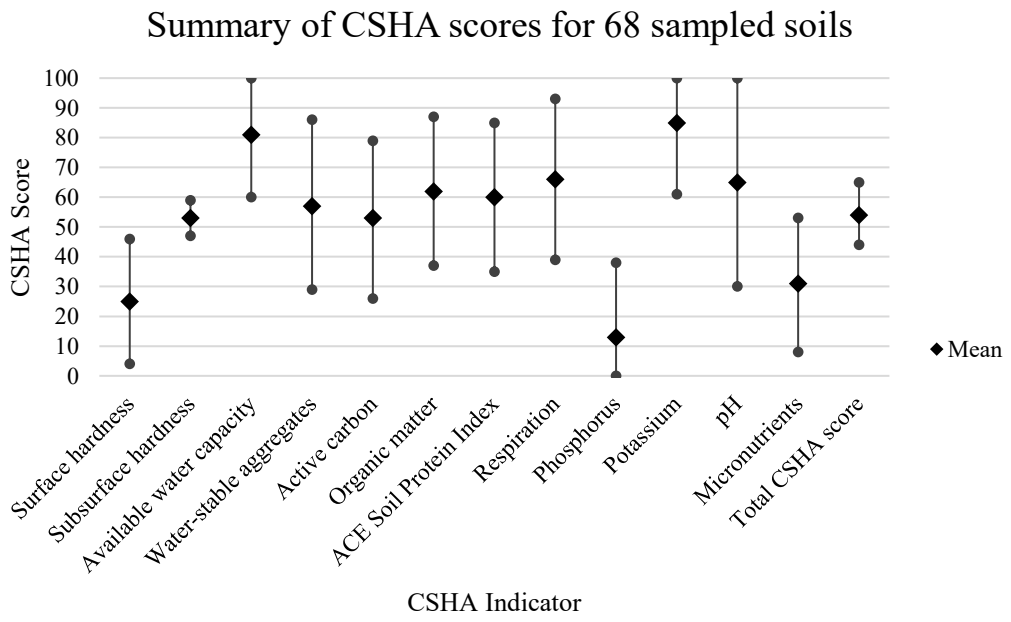


Figure 2. Summary of CSHA Scores for 68 sampled soils: Mean ± standard deviation.

Table 4. Summary of PLFA ratios for 68 sampled soils.

	Good fields		Poor fields	
	Mean	SE Mean	Mean	SE Mean
Fungi/Bacteria Ratio	0.102	0.004	0.103	0.003
Predator/Prey Ratio	0.069	0.005	0.069	0.007
Gram Pos./Gram Neg. Ratio	0.730	0.028	0.770	0.033
Sat./Unsat. Ratio	0.996	0.024	1.038	0.030
Mono/Poly Ratio	9.430	0.502	9.149	0.562

No significant differences between good and poor fields.

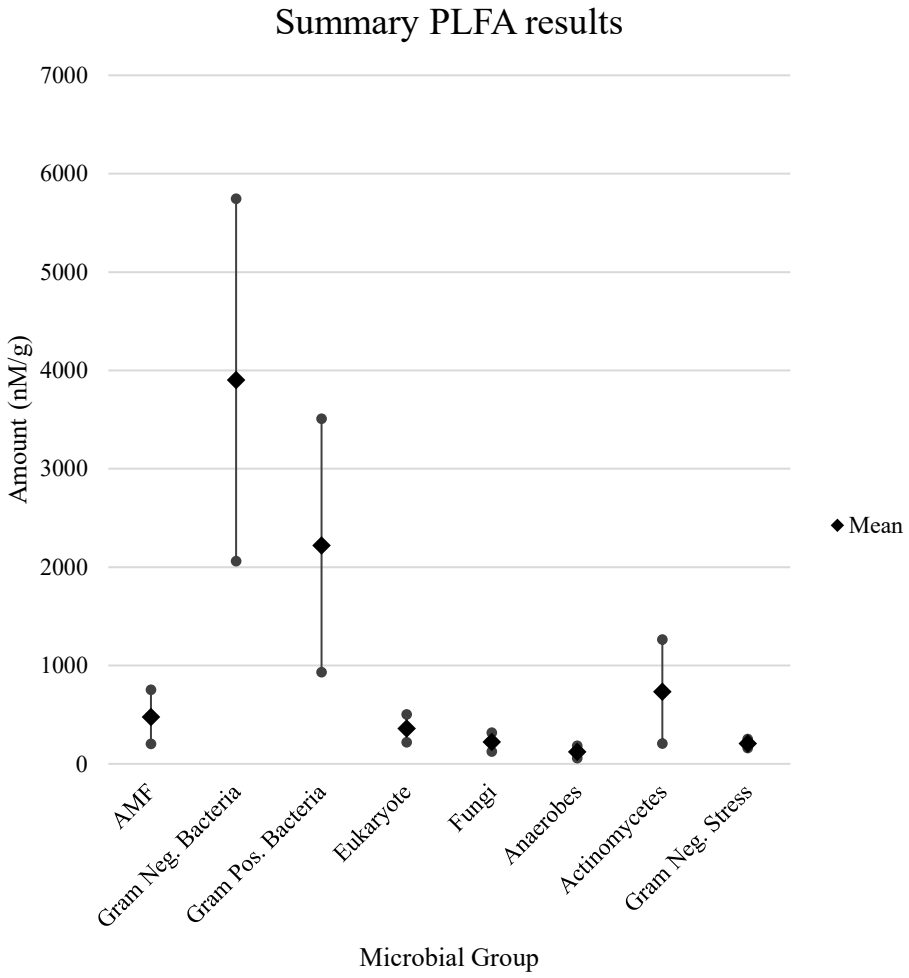


Figure 3. Biomass of various microbial groups for 68 sampled soils: Mean ± standard deviation (nM/g).

4.2. Data Reduction: PCA for Scores 1 and 2 of the three data sources

Biplots and loads of the variates for PCA Scores 1 and 2 of the PCAs for Chem, CSH and PLFA can be found in Appendix B. PCA Scores 1 and 2 from these three original PCAs were combined in a subsequent PCA. PCA Score 1 for CSH and PLFA data as well as PCA Score 2 for Chem data were correlated along PCA Score 1, which accounted for 46% of the variation in fields (Figure 4). Correlations between PCA Scores 1 and 2 for Chem, CSH and PLFA shown below (Figure 5). There was strong positive correlation between 1CSH, 1PLFA and 2Chem, and between 2CSH and 1Chem.

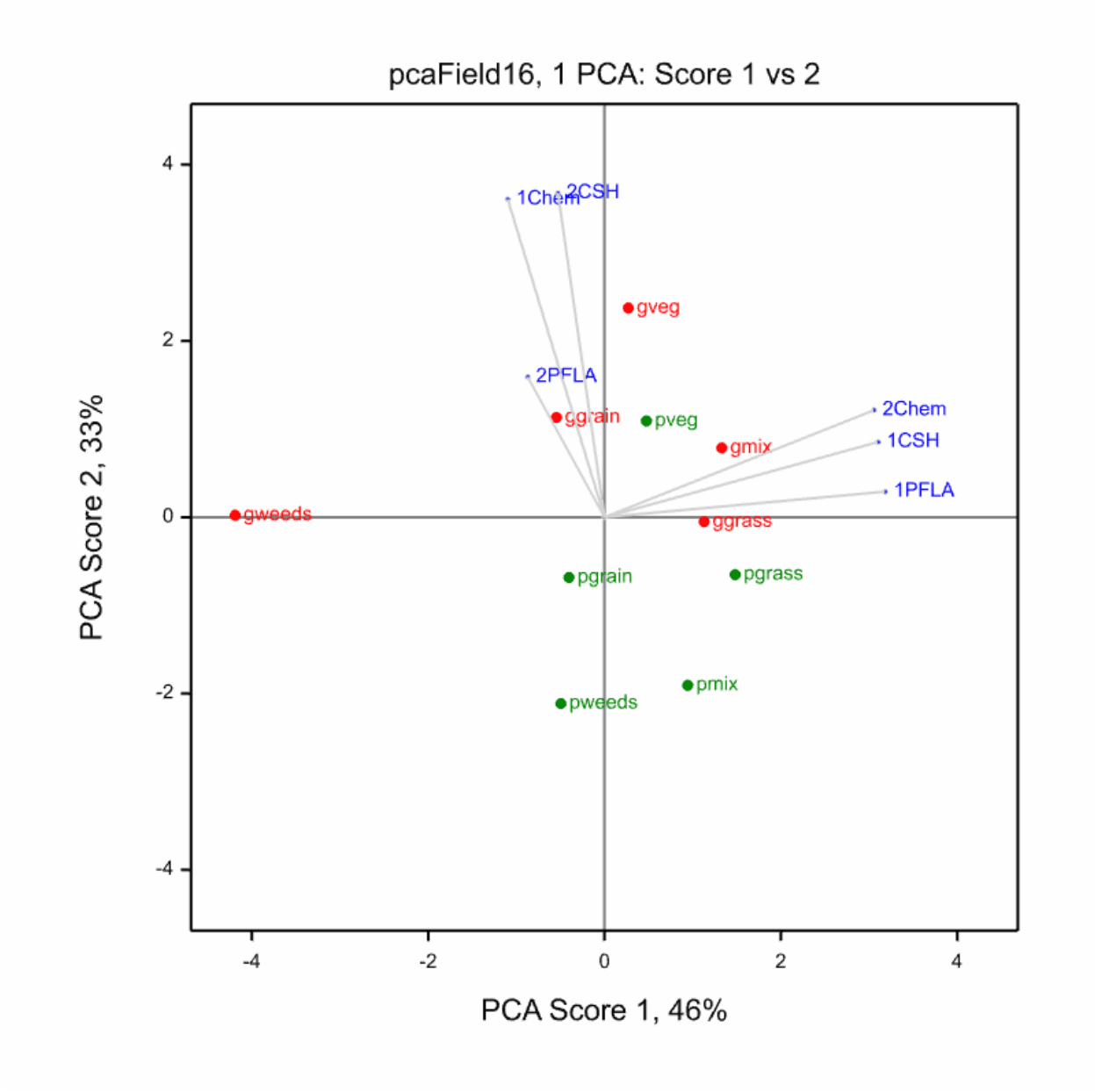


Figure 4. Data reduction PCA biplot using PCA Scores 1 and 2 from initial PCAs on Chem, CSH and PLFA data. Rotations are "g" (farmer-selected "good") or "p" (farmer-selected "poor"): ggrain (n=6), pgrain (n=7,) ggrass (n=11), pgrass (n=11), gmix (n=4), pmix (n=2), gveg (n=12), pveg (n=8), gweeds (n=1), pweeds (n=6).

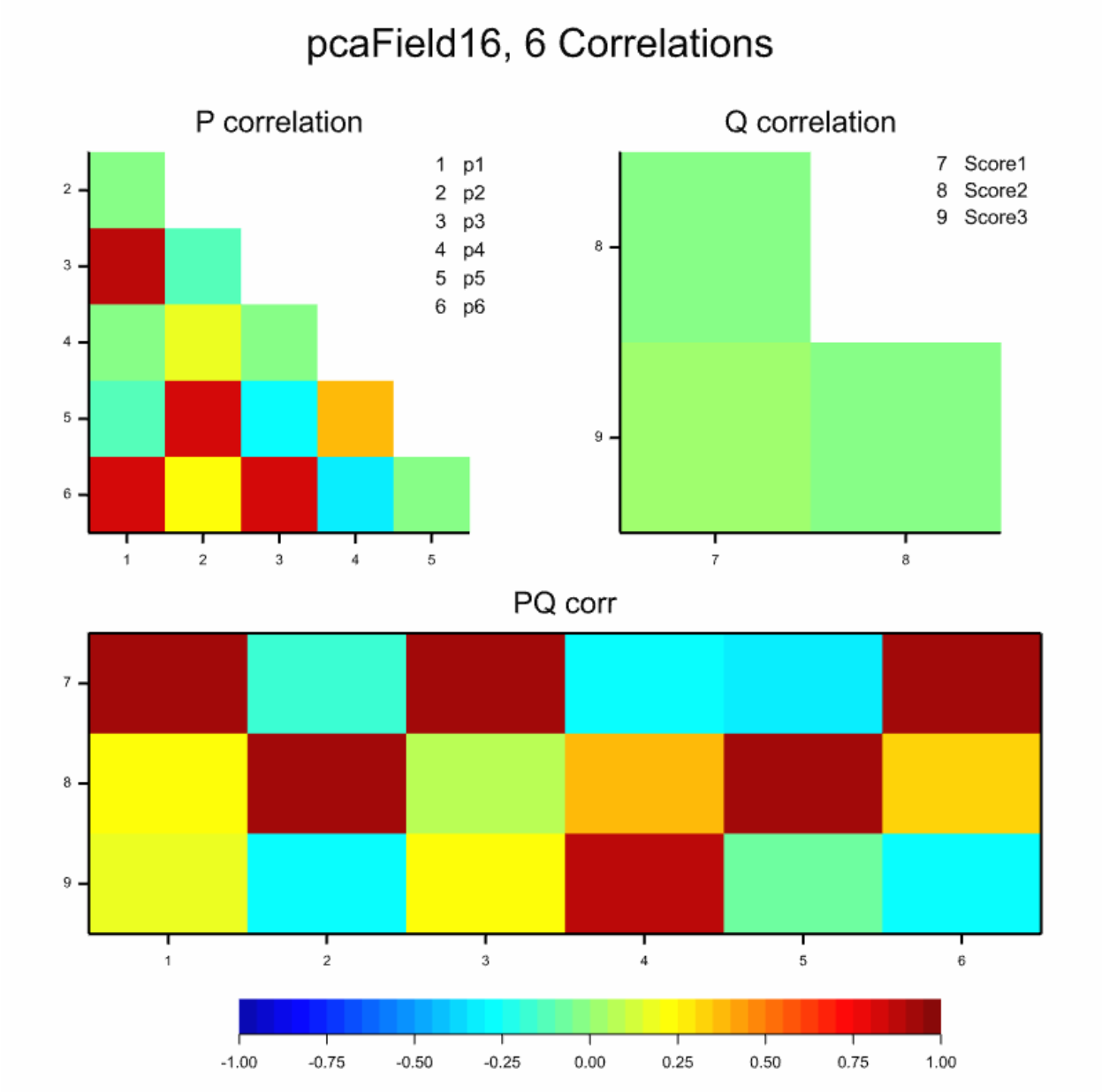


Figure 5. Data reduction correlations between variates (PCA Scores 1 and 2 from original PCAs on Chem, CSH and PLFA data - P correlation), between PCA Scores 1, 2 and 3 (Q correlation), and between variates and PCA scores (PQ corr).

4.3. Final PCA

Based on the above analyses, a final PCA was performed on PCA Score 1 from CSH and PLFA, and PCA Score 2 from Chem. Environmental data (soil texture) and some management factors were included in the analysis, although herbicides, pesticides and fungicides were excluded because of skewing that collapsed the analysis. PCA Score 1 accounted for 65% of variation, PCA Score 2 for 13%, and PCA Score 3 for 9% (not shown) (Figure 6). Fields designated as "good" by the farmer and in a recent rotation of "weeds" ("gweeds") were very different from all other field types, both good and poor. However, only one field fell into this category. Good and poor fields did not differ significantly from each other in any of the other rotations (grass, veg, grain or mix), i.e. ggrass and pgrass were not significantly different from each other. PCA Score 1 shows that the best rotations were grass and mix, with veg and grain being only slightly lower. CEC, active C, ACE protein, OM, Mg and Mn were all positively correlated with each other.

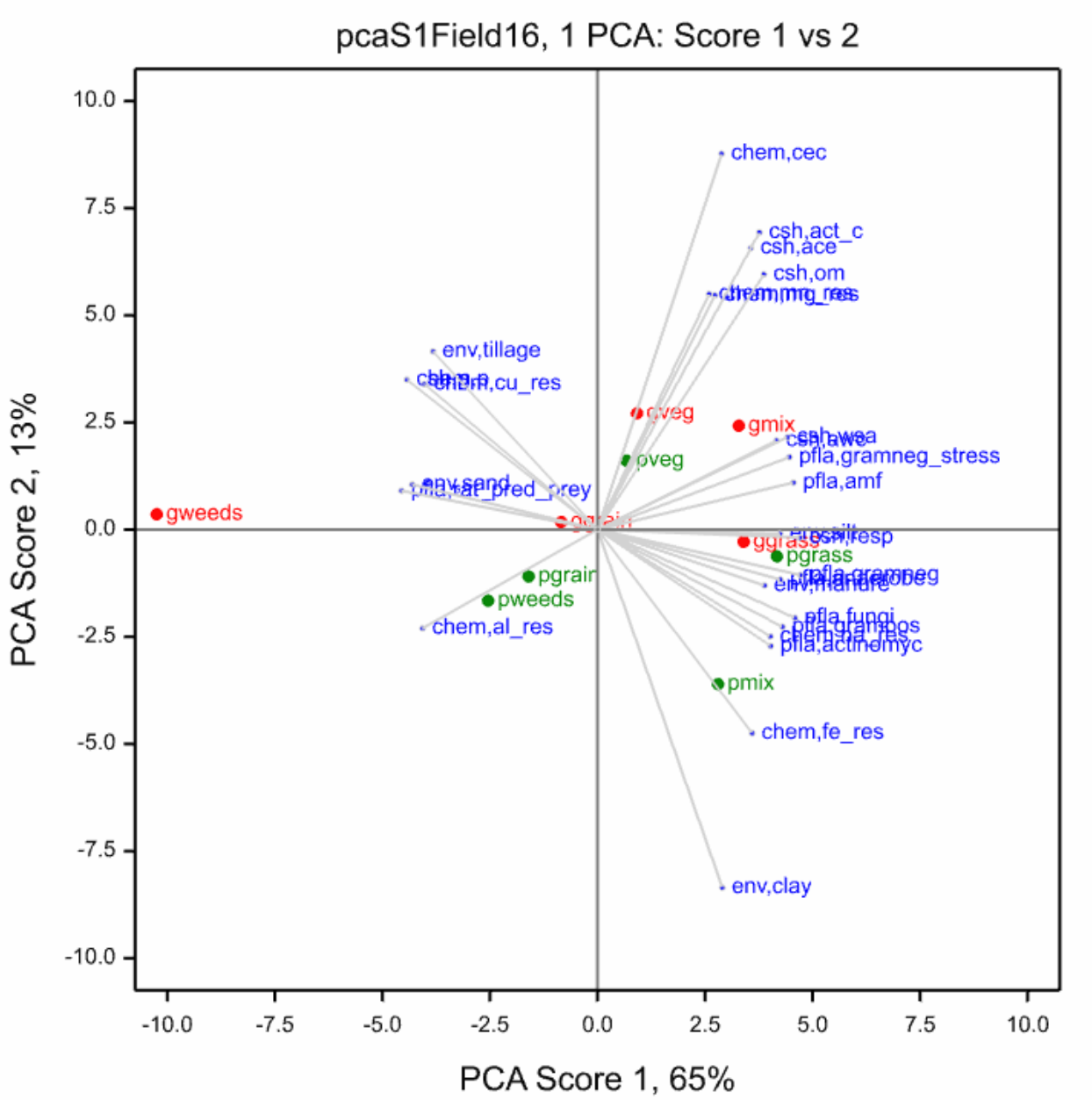


Figure 6. Biplot for final Principle Component Analysis using variates from PCA Score 1 for PLFA and CSH data, and PCA Score 2 for Chem data. Rotations are "g" (farmer-selected "good") or "p" (farmer-selected "poor"): ggrain (n=6), pgrain (n=7,) ggrass (n=11), pgrass (n=11), gmix (n=4), pmix (n=2), gveg (n=12), pveg (n=8), gweeds (n=1), pweeds (n=6).

Most variates correlated more strongly with PCA Score 1 than with Scores 2 or 3

(Figures 7 and 8). PCA Score 1 generally had very high loads for all variates. Most variates

were positively correlated on PCA Score 1, notably including soil respiration, AMF, gram negative bacteria, gram-negative stress indicator, fungi and WSA; negative correlations included P, Cu, Al, sand and the predator:prey ratio. The management factors tillage and manure application were inversely related along PCA Score 1, with tillage negatively correlated and manure application positively correlated with many biological measures. PCA Score 2 was dominated by CEC (positive) and clay (negative), which were the main sources of spread between good fields (higher CEC, lower clay) and poor fields. Clay and CEC were positively correlated on PCA Score 1 but loaded higher on PCA Score 2; CEC and clay content were therefore less important according to PCA. Active C, ACE protein and OM were also positively correlated with CEC on PCA Score 2; clay and Fe were negatively correlated.

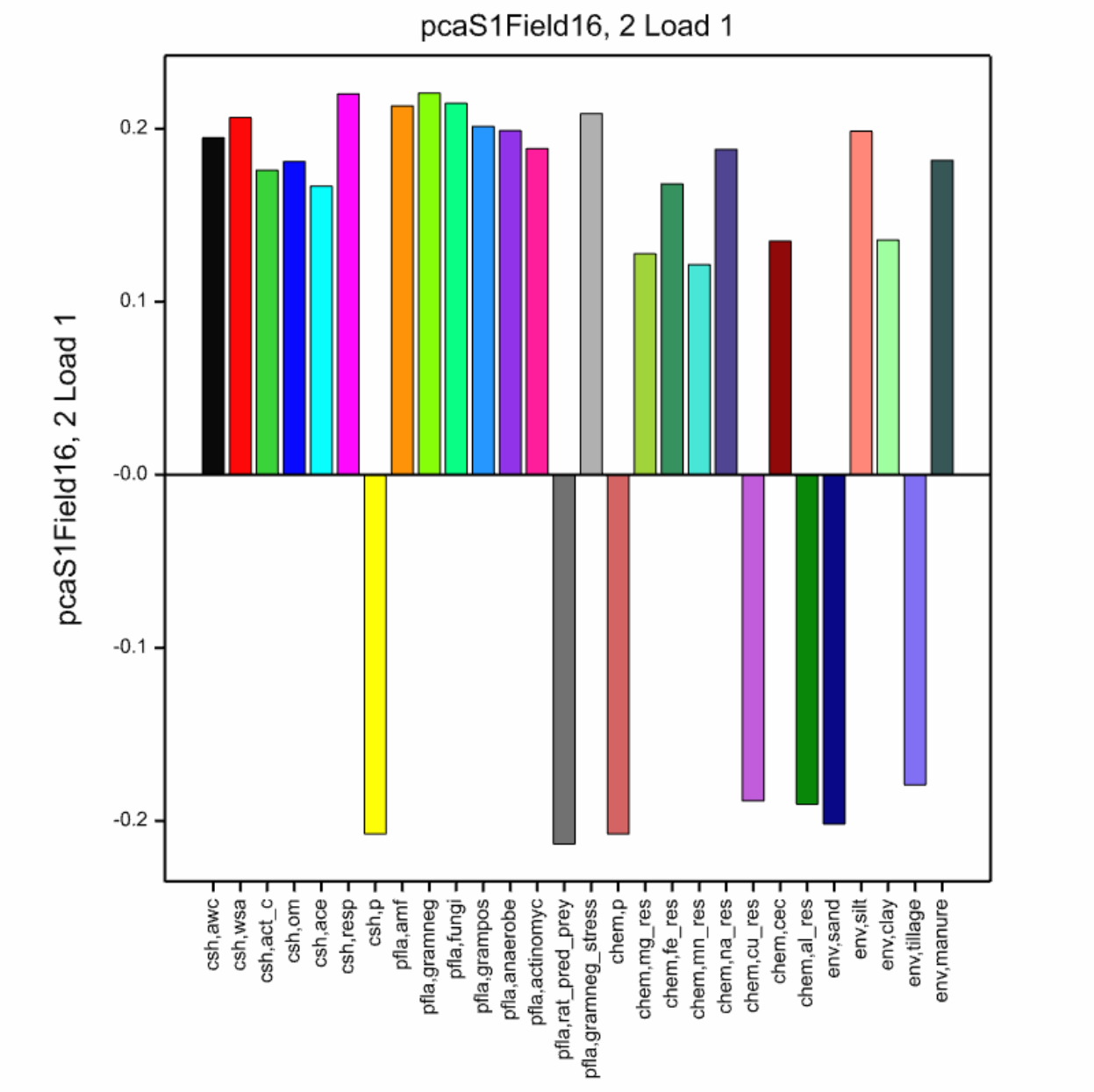


Figure 7. Final PCA loads for Score 1.

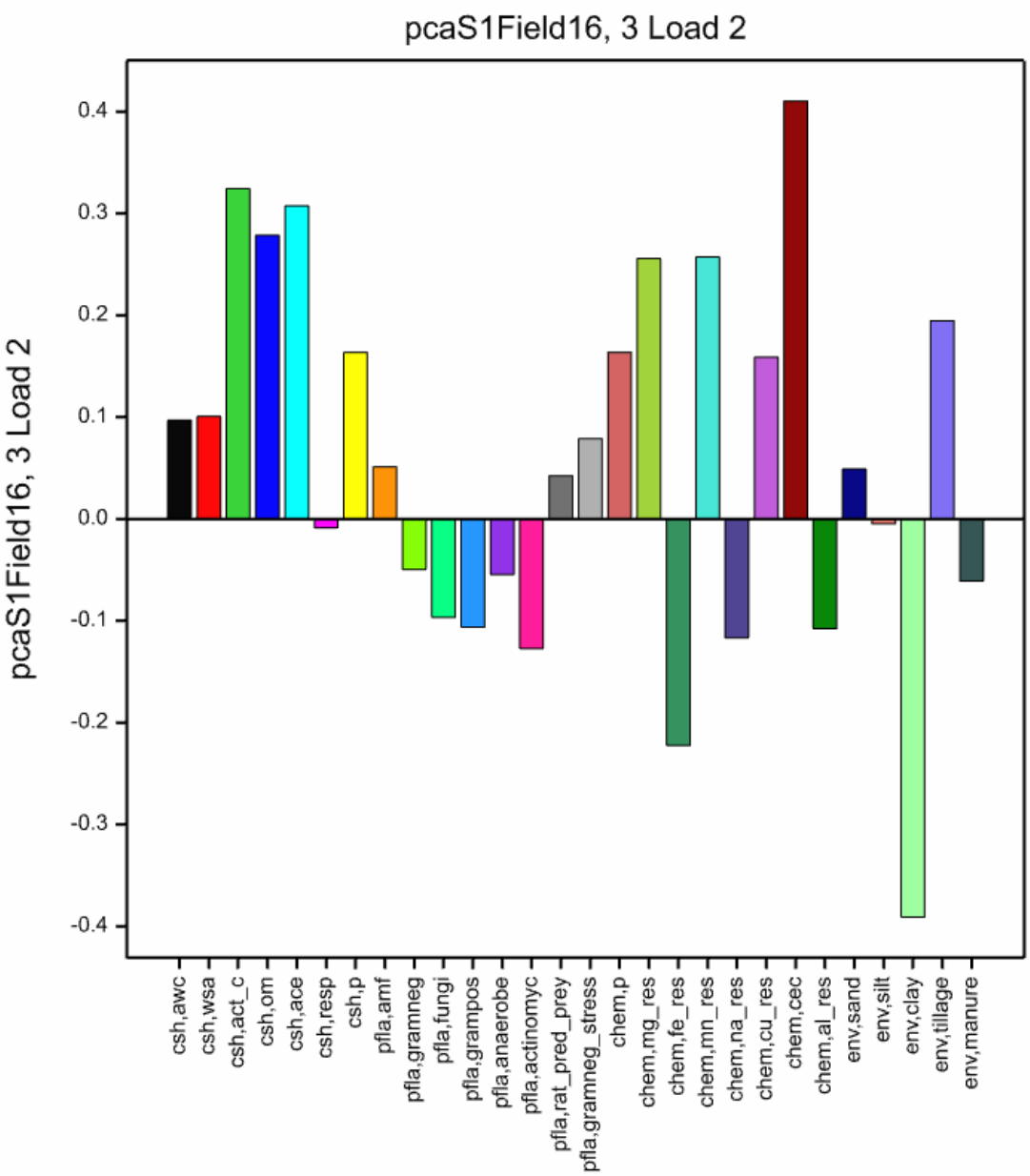


Figure 8. Final PCA loads for Score 2.

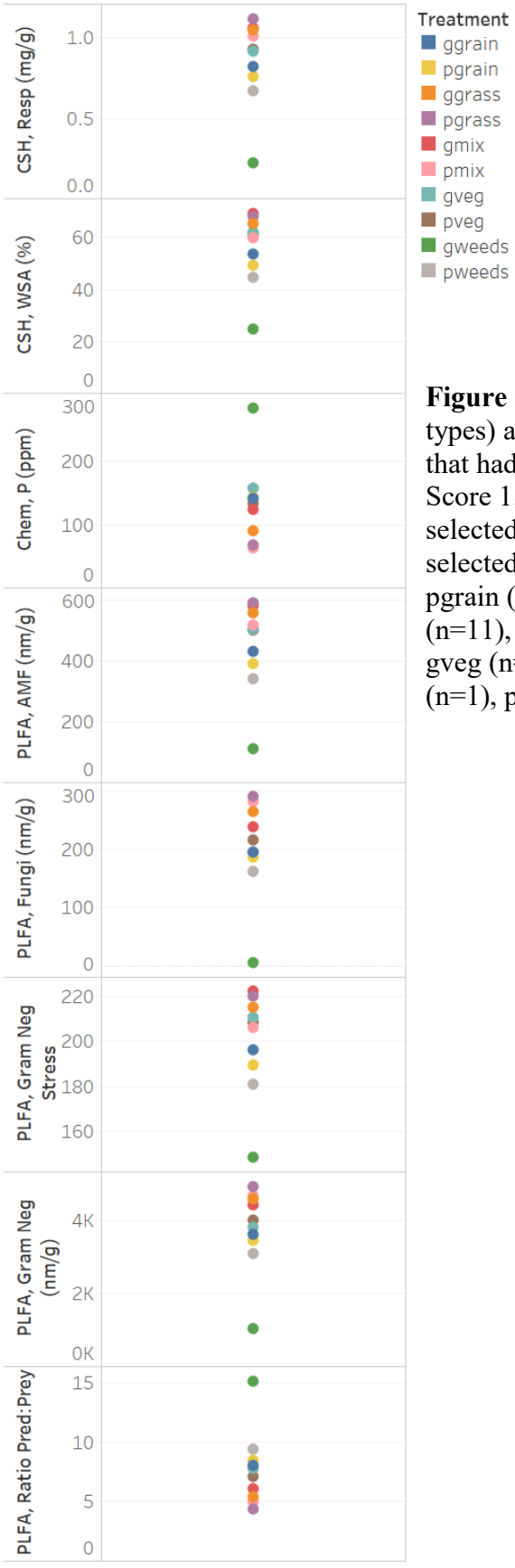


Figure 9. Spread of rotations (field types) along vectors of soil factors that had the highest loads on PCA Score 1. Rotations are "g" (farmer-selected "good") or "p" (farmer-selected "poor"): ggrain (n=6), pgrain (n=7,) ggrass (n=11), pgrass (n=11), gmix (n=4), pmix (n=2), gveg (n=12), pveg (n=8), gweeds (n=1), pweeds (n=6).

Although gweeds presents as significantly different from other field types on all factors, the fact that only one field was included in this category limits the usefulness of this finding (Figures 9 and 10). Other field types generally grouped together more tightly, although some key patterns emerge. Fields in perennial grass had higher levels of soil respiration, WSA, fungi and AMF, and lower soil-P. Mixed fields also followed this pattern, though lower than grass; veg and grain fields, which had higher soil-P and ratio of predators:prey were lower in soil respiration, WSA, AMF, etc. In general, good and poor fields in the same rotation were similar.

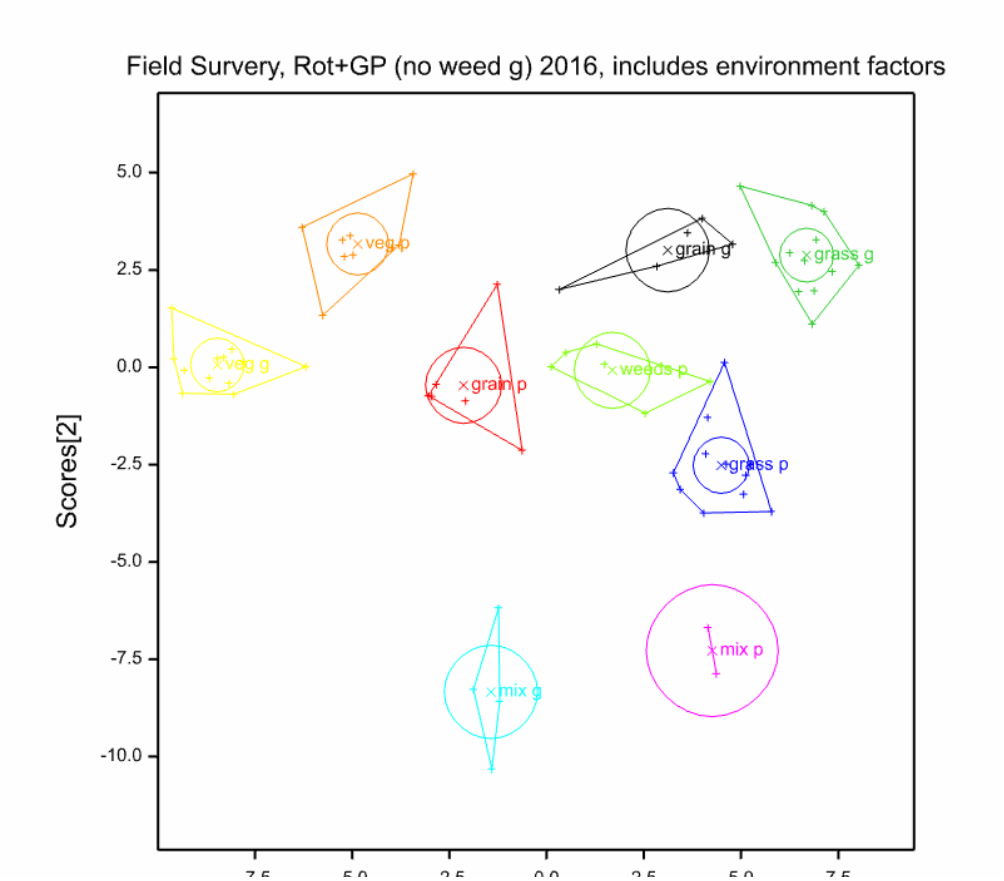


Figure 10. Relative locations of rotations along PCA Scores 1 and 2, excluding gweeds. Rotations are "g" (farmer-selected "good") or "p" (farmer-selected "poor"): ggrain (n=6), pgrain (n=7,) ggrass (n=11), pgrass (n=11), gmix (n=4), pmix (n=2), gveg (n=12), pveg (n=8), pweeds (n=6).

4.4. *Folsomia candida* Bio-assay

CSHA scores for the 12 selected soils ranged from 30-77 (Table 5). *F. candida* survived in every sample through the 23-day incubation (Table 6), and there was a weak but non-significant positive correlation between survival and growth (r=0.26, p=0.37). Survival was poorest on the sand-alone control and sample NS12G (30%) and was highest for sample PE07P (90%).

Table 5. CSHA test values for the twelve selected samples in the F. candida bio-assay.

ID	NB02G	NB03P	NB05P	NB07P	NB09G	NS02P	NS06P	NS07P	NS12G	PE07P	PE13P
Province	NB	NB	NB	NB	NB	NS	NS	NS	NS	PE	PE
Sand (%)	54	57	58	43	58	20	73	79	59	68	61
Silt (%)	39	32	36	46	33	62	20.	17	36	25	30
Clay (%)	7	10	6	11	4	18	7	4	5	8	9
Texture class	Coarse	Coarse	Coarse	Medium	Coarse	Medium	Coarse	Coarse	Coarse	Coarse	Coarse
Surface hardness (PSI)	300	271	273	167	218	224	295	218	300	288	297
Subsurface hardness (PSI)	300	300	300	298	292	294	300	300	300	300	300
AWC (g/g)	0.29	0.19	0.17	0.18	0.17	0.29	0.12	0.11	0.31	0.11	0.23
WSA (%)	77	42	90	59	75	58	12	45	90	27	48
Active C (mg/kg)	887.07	124.72	703.87	422.96	568.6	1103.2	462.74	118.54	980.35	341.88	441.33
OM (%)	7.5	1.6	4.8	4.4	4.2	18.7	2.6	1.4	5.5	0	2.6
ACE (mg/g)	14.61	4.23	10.51	7.07	8.73	26.40	7.12	3.57	20.19	5.54	7.24
Respiration (mg/g)	1.09	0.15	1.10	1.21	0.88	1.40	0.40	0.21	1.20	0.47	0.70
P(ppm)	21	22	28	9	57	26	232	286	43	235	291
K (ppm)	48	25	42	42	49	160	129	166	37	181	115
pH	6.4	5	6.3	5.5	5.8	5.6	6.1	6.5	6.8	6.5	5.7
Mg	344	35	150	72	102	882	205	156	322	67	80
Fe	193	124	241	285	203	474	523	167	169	163	214
Mn	30	14	111	24	64	30	49	62	31	61	31
Zn	1.3	0.7	1.3	0.8	1.8	4.7	4.9	3.1	1.4	1.3	3.1
CSHA score	77	31	61	59	51	71	41	33	70	35	46
CSHA rank	High	V. low	Medium	Medium	Low	High	Low	V. low	High	V. low	Low

Table 6. *F. candida* survival and final body length following 23-day trial.

Treatment substrate	Survival	Average final body length (mm)
PE07P	90%	0.585
NS07P	80%	0.525
PE13P	70%	0.761
NB03P	70%	0.667
NB05P	70%	0.576
Yeast + sand	60%	0.975
NS02P	60%	0.746
NB09G	60%	0.523
NB07P	50%	0.667
NS06P	50%	0.631
NS05P	50%	0.527
NB02G	50%	0.509
NS12G	30%	0.486
Sand	30%	0.474

Growth data satisfied the assumptions of normality and constant variance and did not need to be transformed. Mean body length increased on every treatment substrate (Figure 11). Substrate significantly affected growth during the test period ($p<0.001$), with the greatest growth on the yeast + sand treatment. Tukey distinguished only two significantly different groups: the yeast + sand treatment was grouped with samples PE13P and NS02P, and all soil samples were grouped together with the sand only control (Figure 11). There was no significant correlation between *F. candida* growth and the CSHA score. *F. candida* growth was significantly correlated with clay content (r=0.796, $p=0.003$) and significantly negatively correlated with pH (r=-0.718, $p=0.013$). Growth was weakly positively correlated with OM (r=0.295, $p=0.379$), and negatively with sand (r=-0.473, $p=0.142$) and WSA (r=-0.418, $p=0.201$), although none of these were significant. Correlations with other CSHA measures

were not significant, and there were no significant correlations between *F. candida* growth or survival and any PLFA indicators.

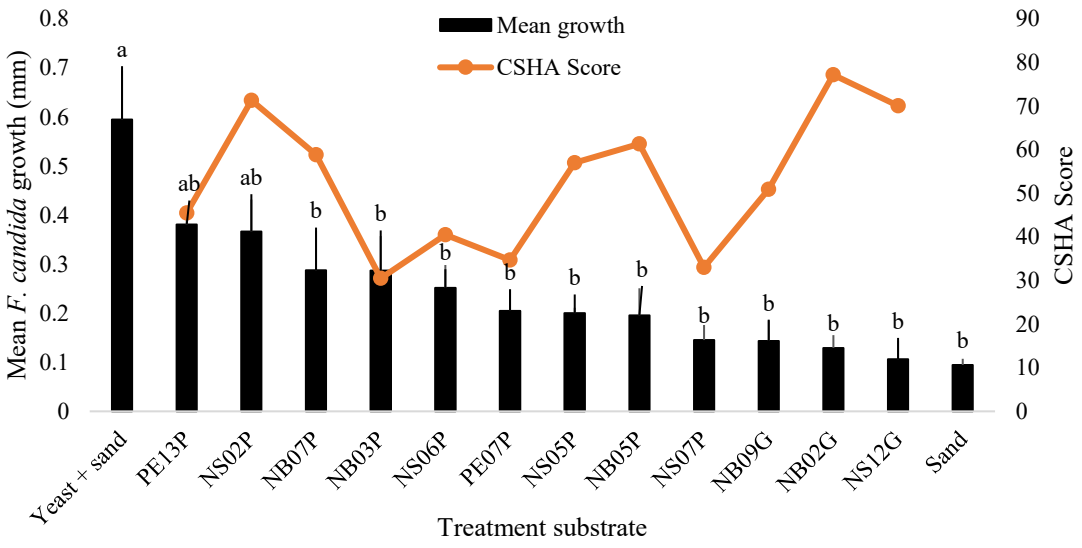


Figure 11. Mean growth and standard error of 1-day old neonate *Folsomia candida* after 23 days' exposure to treatment substrates. Treatments sharing the same letter are not significantly different at p=0.05.

5. Discussion

5.1. *F. candida* and Soil Health

The objective for this chapter was to evaluate the CSHA, PLFA and the bio-indicator *F. candida* test for assessing soil health in Maritimes agricultural fields. Comparison of the *F. candida* bio-assay to CSHA scores was accomplished by comparing *F. candida* growth on twelve diverse soils using one-way ANOVA and Tukey multiple means comparison. As recommended by Nelson et al. (2011), 1-day old neonates were used in a 23-day incubation to assess substrate-effects on *F. candida* growth. Final body length obtained on the Yeast + sand control treatment (0.975 mm) was smaller than that of Nelson et al. (2011) after 23 days,

where length was approximately 1.5 mm. Survival was also slightly lower, ranging between 30-90% here and 40-100% for Nelson et al.

Although there was a significant difference in *F. candida* growth between different substrates, the variation did not reflect CSHA scores for the soils; thus, hypothesis 1.1 was not confirmed. This disagreement between CSHA scores and *F. candida* growth may reflect a lack of sensitivity in the *F. candida* bio-assay or problems in the CSHA scoring system for this region, as discussed further below. While Nelson et al. (2011) found a significant growth difference between all substrates, only two groups were statistically separate here (Figure 11). The yeast + sand treatment was grouped with PE13P and NS02P, and all soil samples were grouped with the sand-alone treatment. Although the soils ranged in CSHA scores and were subject to diverse management practices, all were mineral agricultural soils, and were more similar to each other than those used by Nelson et al. (2011), where an intense potato rotation was compared to decomposed manure and forest soils, which could explain the non-significant results.

Growth was positively correlated with clay content, and weakly correlated with OM; growth was negatively correlated with pH, and weakly negatively correlated with sand. A negative correlation with pH seems atypical (e.g., Kaneda & Kaneko, 2002; Nelson, 2008), and it is unclear why this relationship would appear. Greatest growth was on PE13P, NS02P, NB07P and NB03P, whose pH's were the lowest of the group at 5.7, 5.6, 5.5 and 5.0 respectively. Perhaps the overall pH range (5.0-6.8) was narrow enough that variation within was incidental; Nelson et al.'s soils ranged from pH 3.88-7.22, a much wider range. No correlation was found between soil respiration – an indicator of biological activity – and *F. candida* growth, which is supported by findings from Kaneda & Kaneko (2002). OM was

only weakly correlated with *F. candida* growth; others have suggested that microbial biomass C, a food source for *F. candida,* is more important than total C (Nelson et al., 2011; Doran et al., 1996; Kaneda & Kaneko, 2002). However, there was no correlation found here between *F. candida* growth and any of the PLFA indicators, including total microbial biomass.

5.2. CSHA, PEI Provincial Lab Data and PLFA Analysis

PCA was used to visualise covariance between CSH, Chem and PLFA data and shifts in soil factors with management practices. Three years of field history data was provided by the farmers and categorised (Table 2). PCA was first used as a data reduction technique on the Chem, CSH and PLFA data sources (Appendix B); PCA Scores 1 and 2 for each of these were then combined in a subsequent PCA (Figures 4 and 5). Because PCA Score 1 of PLFA and CSH and Score 2 of Chem were correlated and accounted for 46% of data, these scores were combined in a final PCA using the original variates (Figures 6-10).

Hypothesis 1.2 was confirmed, as shifts in the PLFA profile were associated with CSHA indicators. The final PCA (Figure 6) showed that the CSHA indicators WSA and soil respiration positively correlated with all PLFA microbial groups, most notably AMF, gram negative bacteria, gram-negative stress indicator, and fungi; these correlated negatively with P, Cu, Al and the predator:prey ratio. Though this is the first known comparison of PLFA profiles to a more comprehensive suite of soil health tests, several of the reported relationships are supported in the literature. It is well established that AMF are typically negatively correlated with soil-P (Hijri et al., 2006; Gosling et al., 2013; Bainard et al., 2014; Bainard et al., 2015; Schneider et al., 2015). AMF are also known to aid stabilization of soil

structure through physical enmeshing of soil particles by mycorrhizal hyphae and the exudate glomalin, by affecting plant root exudates, and by increasing overall soil carbon (Rillig and Mummey, 2006; Daynes et al., 2013), thereby confirming the positive relationship between WSA and AMF. Soil respiration, an indicator of soil biological activity, was positively associated with increases in all microbial groups. Heavy metals such as Cu and Al have a negative effect on soil microbial biomass and activity, as highlighted here by the inverse relationship between these metals and all biological soil indicators from the CSHA and PLFA (Illmer et al., 1995; Gillera et al., 1998; Vogeler et al., 2008).

The spread of field types along the most important soil factors (Figures 9 and 10) illustrated clear trends which confirmed Hypothesis 1.3 that changes in CSHA and PLFA soil factors could be linked to management changes. Most notably, perennial grass fields had higher respiration, WSA, fungi and AMF, and lower P. Mixed fields were also higher than other field types, though not as high as grass. Fields which were high in P and the PLFA predator:prey ratio were lower in respiration, WSA, fungi and AMF. These high P fields generally reflected those that would have been more intensively managed, namely grain and veg fields. However, there were no clear differences between farmer-identified "good" and "poor" fields within any of the rotation types except for "gweeds", which was significantly different from every other field type. Given that only one field fell into this category, this finding is anecdotal at best; however, it is interesting to consider why those fields that farmers chose as exceptionally poor were not rated lower by the laboratory soil health tests. This is a question that will be further explored in the following chapter.

Although some individual management factors were excluded from the analysis because of skewing, including herbicides, pesticides and fungicides, other factors were related

to changes in soil factors. Tillage and manure application were inversely related along PCA Score 1, with tillage correlated with P, Cu, Al, sand and the predator:prey ratio, and manure correlated with biological measures like soil respiration, AMF, gram negative bacteria, gram-negative stress indicator, fungi and WSA. In this study, manure was applied most often on dairy farm fields that were in hay or pasture, which explains the inverse relationship between tillage and manure application. Tillage is known to break down macroaggregates and release SOC, thereby affecting biological soil health indicators (Moebius et al., 2007; Acin-Carrera et al., 2013; Sağlam et al., 2015). OM-inputs are known to improve a variety of soil physical and biological indicators, and manure application in particular has been shown to increase SOM, active C and AWC (Iqbal, van Es & Anwar-ul-Hassan, 2014).

The second part of Hypothesis 1.3, that CSHA and PLFA shifts would be linked to environmental factors, was also confirmed. Soil texture was an important factor in the analysis: sand content had a high negative load on PCA Score 1, and clay had a high negative load on PCA Score 2. Sand was inversely related to soil respiration, AMF, gram negative bacteria, gram-negative stress, fungi and WSA, but positively correlated with P, Cu, Al, and the predator:prey ratio. Along PCA Score 2, clay was inversely correlated with CEC, active C, ACE protein and OM. However, because clay had a lower load on PCA Score 1, it explained less variability through PCA.

Soil texture is a determinant for many other soil health indicators such as OM, aggregation, nutrient available, water-holding capacity, and compaction, which is why the CSHA accounts for texture in its scoring functions. Clay content plays a large role in determining CEC and the soil's ability to retain nutrients and OM, as well as form aggregates. Congreves et al. (2015) also found that sand was positively correlated with P and inversely

related to biological indicators like OM and Active C, although they deemed sand less important for future OSHA work because it occurred primarily on PC2.

Overall, the link between CSHA and PLFA indicators is a valuable finding for the possibility of integrating these two measures. It may be possible to use PLFA to explore more in-depth aspects of soil biology, both structural and functional, in concert with the biological, physical and chemical components measured in the CSHA. For example, PLFA is efficient for rapid screening of the microbial community and is useful for describing movement of substrates through the soil food web, for determining bacterial:fungal ratios, for measuring microbial biomass (both total, and by group) and for providing some indication of cell activity and cell stress. Linking PLFA with the CSHA may develop a deeper understanding of how microbial structure and function are affected by a wider range of soil health factors.

5.4. Critiques of the CSHA for the Maritimes

5.4.1. CSHA Laboratory Procedures

Several changes to CSHA laboratory procedures could help improve the reliability and applicability of the results for the Maritimes. First, as in this study, Mehlich-3 extractions rather Morgan extractions should be used for nutrient analyses, to match with current provincial lab test procedures and improve comparability of results. Second, measuring OM by converting C measures from a combustion analyzer would help improve reliability, as the accuracy of loss on ignition (LOI) is affected by furnace type, sample location in the furnace, sample mass, duration and temperature of ignition, and soil texture (Hoogsteen et al., 2015).

The soil respiration protocol was also troublesome. Regardless of soil type, 7.5 mL of distilled deionized water is added to the sample – however, depending on factors such as soil texture, OM and water-holding capacity, this amount of water sometimes over-saturated the sample, making it "mucky". Future soil respiration protocols should specify, for example, that the sample be brought to 80% of field capacity.

5.4.2. CSHA Scoring Methods

CSHA scoring curves are developed based on a regional database and are not linked to biological or physical thresholds. To better match the CSHA to Maritimes soils, a regional database of soil test results should be developed, out of which Maritimes ranking curves can be generated. Future research should explore the inclusion of specific thresholds based on both production-oriented goals like yield or plant health and environmental thresholds for the provisioning of a wide variety of ecosystem services.

Soil texture plays an important role in the ranking system, as designation into coarse/medium/fine textural classes determines which scoring curve will be used for each soil health indicator. Many of the soils in this study fell closely on the line between medium and coarse textural classes, and often a 1-2% change in texture would have pushed the sample into a different texture category. This 1-2% difference falls below the standard 5% variation that is typically accepted for duplicate accuracy check, thus the scoring system for the sample could be greatly influenced by "allowable" laboratory error. Given that there were no fine-textured soils included in this study, textural classes should be re-assessed to better reflect Maritimes soils.

The overall CSHA soil health score is an average of the individual indicator scores. Congreves et al. (2015) established that the scoring system was more sensitive when indicators were weighted differently; in Ontario, this meant that OM, potentially-mineralizable nitrogen (PMN), WSA, active C, CEC, clay content and K were given higher weighting than root health, pH, P, sand, silt and other nutrients. A weighting system should also be developed for Maritimes soil, where the importance of different factors likely varies.

Congreves et al. (2015) found that pH and most nutrients except K were relatively insensitive indicators of soil health. In a recent soil health meeting with farmers in PEI, the issue of CSHA chemical analyses also was raised as a concern. Some farmers felt that the inclusion of pH and nutrients was counter-intuitive given that these values can be altered relatively quickly with soil conditioners or fertilizers, a topic which is covered further in Chapter 3. However, this point only holds true for "more-is-better" type nutrients; phosphorus, for example, was excessively high in most sampled fields, an issue which *would* require long-term soil health strategizing. In addition, the micronutrient scoring is ill-suited to Maritime soils because iron naturally occurs at high levels, which meant that no field scored higher than 56 even if all other micronutrients were at an ideal level. It would be more useful to include boron and copper in the micronutrient scores, as boron was a micronutrient of concern mentioned by farmers, and copper was a significant differentiator between rotations along Score 1 of the PCA. Sulphur could also be valuable to include as a macronutrient, as this also seemed to be a nutrient of concern for farmers. Future research should explore possibilities for improving the chemical scoring system.

These problems with the rating system are reflected in the relatively narrow range of CSHA scores in this study (from 31-77). No soils were rated "Very High" (>80), and part of

this is certainly related to the generally low scores in micronutrients and P. Although this may limit the strength of the comparison – it would be ideal to be able to compare very high scoring to very low scoring soils – on the other hand, such a limitation is a finding in itself by highlighting certain inappropriate aspects of the CSHA scoring system.

5.5. Weaknesses in the Current Work

Farmers did not always have written records of the past five years of field management, which may have affected the accuracy of the field management data. In addition, the CSHA scoring functions are not available online and have likely been updated between the time of posting their methodology in February 2016 and the current work; therefore, the scoring system used here may not exactly reflect the CSHA's current scoring curves.

Only 68 fields on 34 farms during one growing season were sampled for this study, and thus conclusions drawn from this work are only preliminary. Ongoing work sampling hundreds of fields over multiple years will provide a larger dataset to develop more robust protocol and scoring functions for the region.

6. Conclusions and Recommendations

The *F. candida* bio-assay results did not reflect CSHA scores and did not successfully differentiate between soils, despite significant differences in soil types and management practices. It is possible that although the soils came from various farm types and provinces, they were still similar in that all were mineral agricultural soils. Further research could

explore this question of sensitivity further. PCA successfully related shifts in the PLFA profile to CSHA indicators: in particular, WSA and soil respiration were positively correlated with all PLFA microbial groups, and negatively correlated with P, Cu, Al and the predator:prey ratio. Management and environmental factors were linked to PLFA and CSHA indicators. Notably, grass and mixed fields were higher in soil respiration, WSA, fungi and AMF, and lower in soil-P and the predator:prey ratio. More intensely managed fields like undiversified grain and vegetable rotations showed the reverse trend, with higher P, sand content and the PLFA predator:prey ratio, and lower levels of biological indicators. Manure application was linked to positive physical and biological indicators like respiration, AMF, fungi and WSA, and tillage and sand content correlated with P, Cu, Al, and the predator:prey ratio. Overall, the correlations between changes in CSHA indicators and PLFA profiles shows promise for integrating these two tests for stronger soil health assessment. With some improvements to CSHA methodology as recommended above and further research into the possibilities for more in-depth integration with PLFA – for example, the power to explore trophic cascades of C in conjunction with CSHA soil health indicators – these two tests could provide powerful new insights into soil health on Maritimes farms. Given that farmers' good fields were generally not rated better than their poor fields per the laboratory soil health tests, the next chapter aims to better understand why this discrepancy might occur.

Chapter 3: Maritime Farmers' Soil Health Perceptions and Assessments

1. Introduction

In agriculture, the farmer is the major decision-maker and the primary actor in managing soil health. Although a soil's inherent characteristics play a large role in moderating soil health, land management practices also influence soil health, whether positively or negatively (Doran, 2002). Land management decisions that narrowly focus on one soil function – for example, productivity – may impair soil health and limit the ability of the soil to fulfill its many roles (Doran et al., 1996). High intensity land use including excessive tilling, low complexity of crop rotation, and low organic matter-return to the soil reduces diversity and biomass of soil biota, especially of larger biota (Postma-Blaauw et al., 2010; Tsiafouli et al., 2015), leads to a more bacteria-dominated system (Bardgett & McAlister, 1999; De Vries et al., 2006), and reduces SOM and SOC (Wander & Nissen, 2004; Janzen, 2006; Wilson et al., 2011; Acin-Carrera et al., 2013). High intensity management also affects physical soil characteristics by increasing bulk density (Wilson et al., 2011), reducing water-stable aggregation, reducing macro- and meso-pores, and decreasing water-holding capacity (Moebius et al., 2007; Acin-Carrera et al., 2013). These combined effects increase soil erosion and reduce soil health (Moebius-Clune et al., 2016).

Communication between scientists and farmers has historically been a top-down, passive transfer of knowledge, though participatory approaches are increasing (Carr & Wilkinson, 2005). These participatory approaches represent an opportunity for joint learning and lasting soil health benefits (Lobry de Bruyn & Abbey, 2003), however, challenges arise from differing concerns, knowledge and goals between farmers and scientists (Romig et al.,

1995; Ingram et al., 2010; Schneider et al., 2010). Recognizing the differences in perspective that arise from farmers' social, cultural and environmental norms is important for promoting the adoption of soil health monitoring and management programs (Lobry de Bruyn & Abbey, 2003). Communication between farmers and scientists should consist of a continuous loop of knowledge transfer in which both farmers and scientists are key players (Savard et al., 2014).

Scientists need a better understanding of farmers' soil health perceptions to 1) help them communicate with farmers more effectively; and 2) identify weaknesses in farmers' soil health knowledge to develop more targeted soil health education projects. These insights would help farmers and scientists work together to manage for healthier agricultural soils. Given the relative infancy of the soil health debate – several decades at most – there is still significant fragmentation between disciplines (Doering et al., 2015). There is an increasing diversity in the actors involved withsoil research and regional soil management programs, from academic researchers of diverse backgrounds to extension agents, farmers and politicians. A basic understanding of the differences between soil health definitions and perceptions within and between these groups is critical for developing useful soil health research and effective soil health programs. Scientists bringing the soil health concept into the real world must recognize that farmers have different soil health perceptions, and we must work to minimize misunderstandings on that basis. Scientists must also recognize that if soil health is to be a useful tool for bringing a more complex understanding of soil to the average farmer, farmers will automatically try to fit the term and the concept into their worldview. If farmers cannot make sense of the term for themselves, or if soil health is used as another means for funneling education from top to bottom without the continual and reciprocal

transfer of knowledge advocated by Savard et al. (2014), the soil health concept will likely not reach its full integrative potential.

1.1. Soil Health Perceptions

Academic definitions of soil health often draw on the words of Doran et al. (1996, p.11): "the continued capacity of a living soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, maintain the quality of air and water environments, and promote plant, animal and human health." Soil health is typically understood to differ from soil quality by being a more holistic approach to soil, beyond its ability to function for a given use (Carter, 2002). Soil health definitions range from the reductionist, which incorporate a set of measurable biological, physical and chemical indicators, to the integrative, where the soil is viewed more like an organism, with evolutionary and emergent properties (Kibblewhite et al., 2008). Reductionist definitions are often preferred by soil scientists because they are grounded in measurable soil aspects and compatible with conventional soil tests (Kibblewhite et al., 2008).

Farmers have a broad knowledge of the soil in relation to the entire farm and assess soil from the perspective of working it, while scientists have more in-depth knowledge but may not consider the practical needs of the farm (Ingram et al., 2010). Farmers and scientists may make the same observations but mean different things, for example, both scientists and farmers may describe a soil's texture or colour, but the farmer's assessment comes from the context of working the soil, whereas the scientist responds to a specific question (Ingram et al., 2010). The scale of assessment and the level of detail also differ: farmers are often highly

knowledgeable about their own fields, but have little knowledge of the processes in the larger landscape, whereas scientists tend to treat the entire landscape equally (Ingram et al., 2010).

In one of the few studies assessing farmers' definitions of soil health, Lobry de Bruyn & Abbey (2003) found that Australian farmers associate healthy soils with healthy crops and the absence of soil degradation. Farmers' definitions are typically qualitative, lack specific threshold values (preferring "high" or "good") and focus on observable characteristics such as the look and feel of the soil (Lobry de Bruyn & Abbey, 2003). Although Doran's (1996) definition incorporates environmental factors, farmers focus much more on soil health for crop productivity than environmental sustainability (Lobry de Bruyn & Abbey, 2003). Definitions differ substantially between regions, indicating the importance of local environment and culture on farmers' perceptions. Even though farmers indicated rarely or never using the term soil health, they nevertheless possessed an intuitive sense of its meaning (Lobry de Bruyn & Abbey, 2003).

This intuitive knowledge about soil health is developed through farmers' ongoing observations of the soil at various times of year and under all conditions (Romig et al., 1995). Farmers' soil knowledge is based almost exclusively on sensory observation, with the notable exception of fertility knowledge gained from chemical soil tests (Romig et al., 1995). Because soils are only one of several important resources on the farm, farmers tend to expand their soil assessments beyond soil parameters, for example, by including animal and plant health or water quality, based on typical patterns for their farm (Romig et al., 1995). Though farmers use a wide variety of terms to describe their soils, they tend to recognize soil health on a dichotomous scale: healthy or unhealthy (Romig et al., 1995).

Farmers are far from being a homogeneous group. Different value systems and pressures on the farmer have a major impact on perceptions about soil (Morgan & Murdoch, 2000; Lobry de Bruyn & Andrews, 2016). Adoption of soil health management practices in the United States is influenced by age, education and gender, with younger, female and well-educated farmers being more open to soil conservation practices (Carlisle, 2016). Farmers who employ some type of conservation practices, including organic management, no-till or cover cropping, are more likely to be concerned about in-depth soil analyses (Lobry de Bruyn & Andrews, 2016). In production areas that emphasise productivity and yield, such as the US Corn Belt, farmers tend to make soil management decisions based on economics – there, N fertilizers are applied on almost 100% of land, despite only 30% of farms conducting soil tests (Lobry de Bruyn & Andrews, 2016). The soil health concept has recently been applied in this context as a potential tool for shifting to more sustainable farming practices. The Soil Health Partnership, begun in 2014 by the National Corn Grower's Association with support from such large organizations as Monsanto and the United Soybean Board, is working to explore on-farm opportunities for soil health research and management at the field level in collaboration with local farmers (Karlen, Goeser, Veum & Yost, 2017).

1.2. Farmer Methods for Assessing Soil Health

Farmers typically rely on 3-6 indicators for assessing soil health (Lobry de Bruyn & Abbey, 2003), usually incorporating both technical and qualitative indicators (Kelly, Allan & Wilson, 2009). Overall, research has identified some 90-100 indicators and techniques used by farmers worldwide to assess their soils, ranging from soil colour, drainage and pH to weed presence, seed germination, and presence of pests (Kelly et al., 2009). In Australia, the

preferred indicators were plant growth and the feel of the soil, usually related to its workability, followed by organic matter (Lobry de Bruyn & Abbey, 2003). In Wisconsin, farmers identified a wide range of indicators, incorporating aspects of the biological (earthworms, decomposition), physical (erosion, compaction) and chemical (pH, nutrients) (Romig et al., 1995). Yield was not a primary measure of soil health (Romig et al., 1995), whereas in California, farmers perceived yield to be the defining indicator of soil quality, followed by other indicators such as compaction and biological activity (Andrews, Flora, Mitchell & Karlen, 2003).

Working with Brazilian rice farmers, Lima et al. (2013) assessed soil quality based on 29 indicators, a subset of 8 indicators (the author's minimum dataset), and 4 indicators selected by farmers. Though soil quality was best assessed using the 29 indicators, use of the farmer-selected indicators showed the same trends among management systems, textural classes, and soil functions, indicating that farmers possessed enough soil knowledge to select the most relevant indicators (Lima et al., 2013). Using this farmer-selected set may make the results more accessible for farmers' interpretation (Lima et al., 2013). Liebig & Doran (1999) found that farmers could accurately or near-accurately predict soil parameters 75% of the time for "good" soils, but that farmers' assessments were less accurate for "problem" soils.

Soil testing usually makes up only a small part of a farmers' assessment and is often used to confirm the farmer's soil observations (Kelly et al., 2009). Farmers may even be skeptical of lab soil tests due to experience with conflicting lab results or distrust of the soil testers themselves, especially agricultural companies looking to sell a product (Kelly et al., 2009). This skepticism may be exacerbated by the fact that some farmers rely on agronomists or industry professionals to interpret soil tests for them (Kelly et al., 2009). Farmers who

consult industry agronomists tend to be more focused on the soil's productivity, whereas those engaging with soil scientists take a more holistic approach to soil management (Kelly et al., 2009).

In-field soil health scorecards are a useful tool for farmers to systematically assess their soils without access to specialized equipment. One example is the Wisconsin Soil Health Scorecard, which was developed through extensive farmer interviews about their preferred soil health indicators (Romig et al., 1995). This scorecard incorporates a wide range of indicators to score the soil on factors including chemical, physical and biological measures, as well as plant and animal health. A Canadian example of this is the online soil health test developed by OMAFRA to help farmers rank a diverse suite of soil factors (OMAFRA, 2016).

It is likely that Maritime farmers have their own methods for assessing soil health based on local considerations that differ from other regions. Understanding how farmers define soil health and assess soils on their farms will help scientists in designing soil health education/improvement initiatives and will help scientists understand how best to approach the soil health issue.

1.3. Laboratory Soil Health Analyses

The Cornell Soil Health Assessment (CSHA) was developed by Cornell University and became commercially available in 2006. The test integrates physical, chemical and biological indicators and has been evaluated in several trials in the New York region (Schindelbeck et al., 2008; Idowu et al., 2008; Moebius-Clune et al., 2016). Depending on the

tests selected, each of between 9 and 16 indicators is scored out of 100 and given a colour (red, yellow or green) based on its interpretation as low, medium or high. The soil is also given an overall mark, calculated within soil textural classes, using scoring functions based on the regional database of soils analysed by Cornell University. Thus, the scoring does not necessarily represent real biological or physical thresholds but is a comparison to a regional dataset of CSHA analyses results.

Recent work has attempted to validate the CSHA for use in Canada. Van Eerd et al. (2014) found that the CSHA's assessment of soil health correlated with SOC and total N in Ontario. Congreves et al. (2015) showed through PCA that root health, sand content, Mn, and pH were less valuable as soil health indicators in Ontario, and that weighting the indicators would make the CSHA more sensitive to management. In this chapter, the CSHA serves two purposes: 1) farmers' perceptions of soil parameters such as OM, pH, and biological activity will be compared to CSHA test values; and 2) the overall CSHA score will be compared with farmers' assessments to explore the correlation between farmers' perceptions and a laboratory soil health test, and to explore farmers' reactions about the usefulness of the CSHA.

2. Objectives and hypotheses

Objectives 2 and 3 are addressed in this chapter. Objective 2 was to characterize farmers' perceptions of soil health and understand how farmers assess their own soils. Here, it was hypothesized that 1) farmers' soil health perceptions will reflect their needs and interests on the farm, and will therefore be more management- or production-focused; and 2) farmers'

soil health perceptions will differ between farm types and farmer demographics, as determined through structured interviews.

Objective 3 was to compare farmers' in-field soil health assessments to a laboratory-based soil health assessment (the CSHA). It was hypothesized that 1) the farmer's in-field soil health scorecard and the CSHA will consistently distinguish between 'good' and 'poor' soils on each farm; and 2) farmers will agree with CSHA results for soil characteristics that they are familiar with, such as nutrients levels, and will disagree with CSHA assessments of unfamiliar or novel soil characteristics, based on the ranking of seven parameters common to the in-field scorecard and the CSHA.

3. Methods

Farmers were interviewed about their soil health perceptions and their methods for assessing soil on their farm. They selected two fields for soil sampling on their farm – a 'good' soil and a 'poor' soil – for which the farmers completed an in-field soil health scorecard (see Appendix D). Although farmers were not given the option to op out of selecting a good and a poor soil, they were given the option to select a particular area of a field that they perceived as being better or poorer than the average, for example, an area with poorer drainage than the field overall. Soil samples were analysed in laboratory using the CSHA, as well as phospholipid fatty acid analysis and a *Folsomia candida* bio-assay, as described in Chapter 2. Farmer assessments were then compared to the CSHA to assess commonalities and discrepancies between farmers' soil health assessments and laboratory measures.

As described in Chapter 2, 34 farms were selected across NS, NB and PEI and were visited in late summer, 2016. A map of the farms is shown in Figure 1, Chapter 2, and a breakdown of farm types can be found in Table 1 of that chapter. Briefly, there were 14 organic farms and 20 conventional farms, including vegetable, dairy, field crops and beef/sheep farms. Two fields were sampled on each farm, farmer-selected "good" and "poor" fields, for a total of 68 fields sampled.

3.2. Farm Visits: Interviews and Soil Sampling

Farm visits took place between August 11 and September 16, 2016. Upon arrival on farm, the farmer was asked to identify a 'good' and a 'poor/problem' soil on their farm. These fields were then sampled by one team member using CSHA methods, as described further in Chapter 3. While soil sampling and surface and sub-surface compaction measurements were conducted, the principle investigator interviewed the farmer about his or her soil management practices and ideas about soil health. The interviews always followed the same script, although in some cases follow-up questions were used for clarification where necessary (see Appendix E). Seven main questions were asked:

1. How do you know what is a good soil and what is a poor soil?
2. If we were to walk out to a piece of land right now and look at the soil, what specific things do you look for or think about when trying to assess it?
3. Have you ever made a management decision because you wanted to improve your soil and if so, what was the decision?
4. Do you ever conduct soil testing on your farm? If so, where and how often?
5. How do you use the soil test information?
6. Have you ever heard or read about the term "soil health"?
7. *If Yes*: How would you define soil health?
   If No: How would you define soil quality?

Interviews were recorded and transcribed later using Express Scribe Transcription Software, except in two cases where the farmers declined to be recorded; in these cases, notes were taken by hand. Transcriptions were then loaded into QDA Miner Lite V. 2.0 for coding and analysis. To develop codes, the transcripts were read through and common topics were noted. These topics were then classified into codes and grouped into themes – for example, when discussing soil assessments, farmers might mention 'organic matter', 'earthworms', 'soil life', and 'diversity', which were coded under the theme 'Biological indicators'. Transcripts were then read through again thoroughly and coded in detail.

3.3. Farmer's In-field Soil Health Scorecard

For each of the good and poor soils on their property, farmers were asked to complete an in-field assessment of soil health. The questionnaire was based on the assessment used by Liebig & Doran (1999) and the Wisconsin Soil Health Scorecard with changes made to reflect the most common indicators mentioned by farmers in the online survey. In this way, the scorecard was adapted to represent Maritimes farmers' actual methods for assessing soil health. Seventeen indicators were used, as shown in Appendix D, and farmers rated each indicator as "0", "2", or "4", corresponding to "poor/low", "medium", and "high/good" respectively. The indicators were: texture, colour, workability, compaction, drainage, water holding capacity, soil structure, N, P & K availability, micronutrient availability, OM, pH, earthworm activity, soil smell, plant appearance, root health, biological activity and crop yield. Based on the farmer's rating of the individual soil properties, the soil was given an overall soil health score.

3.4. Soil Health Laboratory Analysis

As described in Chapter 2, the CSHA assesses a suite of chemical, biological and physical soil health indicators: macronutrients (P and K), micronutrients (Fe, Mg, Mn and Zn), pH, OM, soil protein, respiration, active carbon, available water capacity (AWC), water-stable aggregates (WSA), and surface and sub-surface hardness. Nutrient (Mehlich-3 P and K, micronutrients), pH and OM analyses were conducted by the PEI Analytical Laboratory in Charlottetown, PEI. The remaining CSHA procedures were conducted in the Atlantic Soil Health Laboratory at Dalhousie University Faculty of Agriculture in Truro, NS, using Cornell's Standard Operating Procedures (Cornell Soil Health Laboratory, 2016).

3.5. Follow-up Farmer Interviews

Following completion of laboratory soil analyses, the soil test results were returned to the farmers. Follow-up interviews were conducted over the phone during February-April 2017, serving partially as an educational exercise to allow farmers to ask questions about their results and partially to understand farmers' reactions to the soil health analyses. These interviews were less structured than the first round of interviews, because farmers' comments and questions directed the conversation in large part. However, the following questions were used to help steer the conversation:

1. Is there anything here that surprises you?
2. Does this information make sense to you? What part doesn't make sense?
3. How does this compare with what you thought about these soils before?
4. Do you think that you will use this information to change your practices?
a. *Follow-up:* What specific changes do you see yourself potentially making?
5. Would it be useful for you to have this type of testing more available?

6. Do you have any questions or comments about your soil test results?

These interviews were analysed in the same way as the first round of interviews. Interviews were recorded and transcribed using Express Scribe Transcription Software, after which transcripts were transferred to QDA Miner Lite V. 2.0. Codes were developed by reading through the transcripts to note common topics, which were classified into codes and grouped into themes. Finally, transcripts were read through thoroughly and coded.

3.6. Statistical Analyses

Statistical analyses for this chapter were conducted using Minitab version 17 software. Paired t-tests were used to ascertain whether 'good' soils were different from 'poor' soils per the farmers' assessments and the CSHA. Seven specific indicators (water-holding capacity, aggregation, P & K, micronutrients, pH, organic matter and biological activity) were compared based on the farmers' assessment and the CSHA values to ascertain agreement between the two assessments. Compaction was not included, as originally planned, because drought during the sample period significantly hardened the soil and affected the accuracy of the test values. CSHA results were categorized to match the scorecard categories of 0, 2 or 4. In the cases of AWC (corresponding to scorecard Q7), WSA (corresponding to scorecard Q8), and respiration (corresponding to scorecard Q16), high CSHA scores (>70) were marked as "4", medium scores (30-70) as "2", and low scores (<30) as "0" to match the CSHA scoring curves. This method was used for these questions because farmers were not asked to give specific values but rather asked if the soil could be considered 'adequate' or not for these

categories. For pH (corresponding to scorecard Q11) and organic matter (corresponding to scorecard Q12), farmers were asked to select specific test values (i.e., OM is <1%, or pH is <5.5), and categories were developed in the actual soil test values to correspond to the scorecard categories.

The two further exceptions to this categorisation were macronutrients and micronutrients. Whereas the CSHA views P, Fe and Mn as having an optimal range (i.e., more is not necessarily better), this option was not given on the scorecard. Therefore, the soil test values for these nutrients were used under a "more is better" assumption. For macronutrients, a score of 0 corresponded to P & K both being low; 2 corresponded to either P or K being low; and 4 corresponding to both being high. Boron was included as a micronutrient because it seemed to be a nutrient of concern for farmers, and Fe was excluded because it is a naturally occurring element at high levels in the Maritimes. The micronutrients included were therefore zinc, magnesium, manganese and boron. Because only some of these micronutrients are rated by the CSHA, the PEI analytical lab rating levels of Low, Medium, and High were used to develop categories "0", "2" and "4" respectively. To calculate the overall score for micronutrients, these four scores were then added together: a sum of <6 corresponded to "0", 6 -10 corresponded to "2", and >10 corresponded to "4".

If the farmers' assessment and the CSHA assessment were both in the same category, they were considered to be in agreement. Chi-square test for association in Minitab 17 was used to compare the farmers' scorecards to the test values, where the hypotheses were:

H_o: farmers' rating and actual results were independent

H_a: farmers' rating and actual results were dependent

Because both farmers and the CSHA were less likely to give a rating of "0", this sometimes resulted in expected cell values of less than one, violating the assumption that all expected cell values should be greater than one. To combat this, the "0" rating option was sometimes excluded from the analysis, resulting in slightly smaller sample sizes ranging from 52-68.

4. Results

4.1. Online Survey

The 59 farmers who participated in the online survey responded with a total of 73 unique indicators that they used to assess soil, with an average of six indicators each (Appendix F). The indicators were highly diverse and represented biological, physical and chemical indicators. Biological indicators were mentioned slightly more often than others (29% of indicators were biological, 21% physical and 19% chemical). The most commonly mentioned indicators were plant health/growth, nutrients, earthworms, soil organic matter, and drainage (Figure 12). Other commonly mentioned indicators included soil structure, water holding capacity, pH, soil life/microbial activity, and texture. Of these indicators, 18% could be classified as qualitative or intuitive indicators of soil health. For example, farmers mentioned judging soil by its colour, smell, ease of till, balance or richness. In addition, seven indicators were uniquely management-based – the soil was judged not by observed factors, but by known factors of management such as whether tile drainage was present, whether tillage or additives were needed and what the crop rotation history had been.

Figure 12. Most common soil indicators mentioned by 59 Maritime farmers.

4.2. Farmer Interviews

4.2.1. Farmer Demographics

Thirty-four farms were visited for interviewing and soil sampling. The distribution of farms is shown on the map in Figure 1, Chapter 2, with 12 farms in Nova Scotia, 9 farms in New Brunswick, and 13 farms in PEI. There were 14 organic farms and 20 conventional farms of a wide variety (Table 1, Chapter 2).

Farmers ranged in age from 27-70, with an average age of 47. Age and experience did not vary greatly based on farm type or by organic designation, as shown in Table 7. Only eight women participated in the study, seven of whom were organic vegetable farmers and one of whom was a conventional sheep farmer. All but four of the farmers had learned about soil in a formal setting, be it through a course, workshop, seminar, conference, or as part of their college or university education.

Table 7. Average farmer age and experience in years.

	Farmer age	Farmer experience
Vegetable	47	17
Dairy	48	30
Field Crops	47	29
Beef/Sheep	48	12
Organic	49	19
Conventional	46	24
Average	47	22

4.2.2. Question 1: How do you know what is a good soil and what is a poor soil?

Aboveground indicators were mentioned by 91% of farmers in their soil assessments, including plant growth, plant health, yield, weed presence and, in one case, health of the animals grazing on that land (Figure 13). Plant health and vigour was especially important, as described by one organic vegetable farmer:

> "… for example, even the buckwheat that we just planted in between the rows as a cover crop/green manure crop has thicker stems on the good than on the poorer soil… the plants would be more vigorous in the good soil - they're taller… they just look healthier, they have better colour in their leaves." (Farmer NS01).

Farmers also assessed the presence and types of weeds as soil indicators, as certain weeds might indicate soil pH, nutrient availability or drainage. While some farmers mentioned presence of weeds or high plant diversity as positive indicators of soil health, others thought weeds indicated that soil improvements were needed.

Many farmers also noted the difficulties of associating aboveground indicators with soil health because of confounding factors such as management. Healthy soils were sometimes perceived to require fewer management interventions: “To me a good soil is one that grows good crops without me babysitting it the entire time” (Farmer NB04). Others thought that a good soil would react more readily to management factors, as mentioned by a Nova Scotia sheep farmer: “As a farmer, a good soil is some productivity, so … if it reacts to the improvement we do to it and produces more, for me that would be a good soil. A poor soil is something that you cannot ever improve to have a decent productivity” (Farmer NS12).

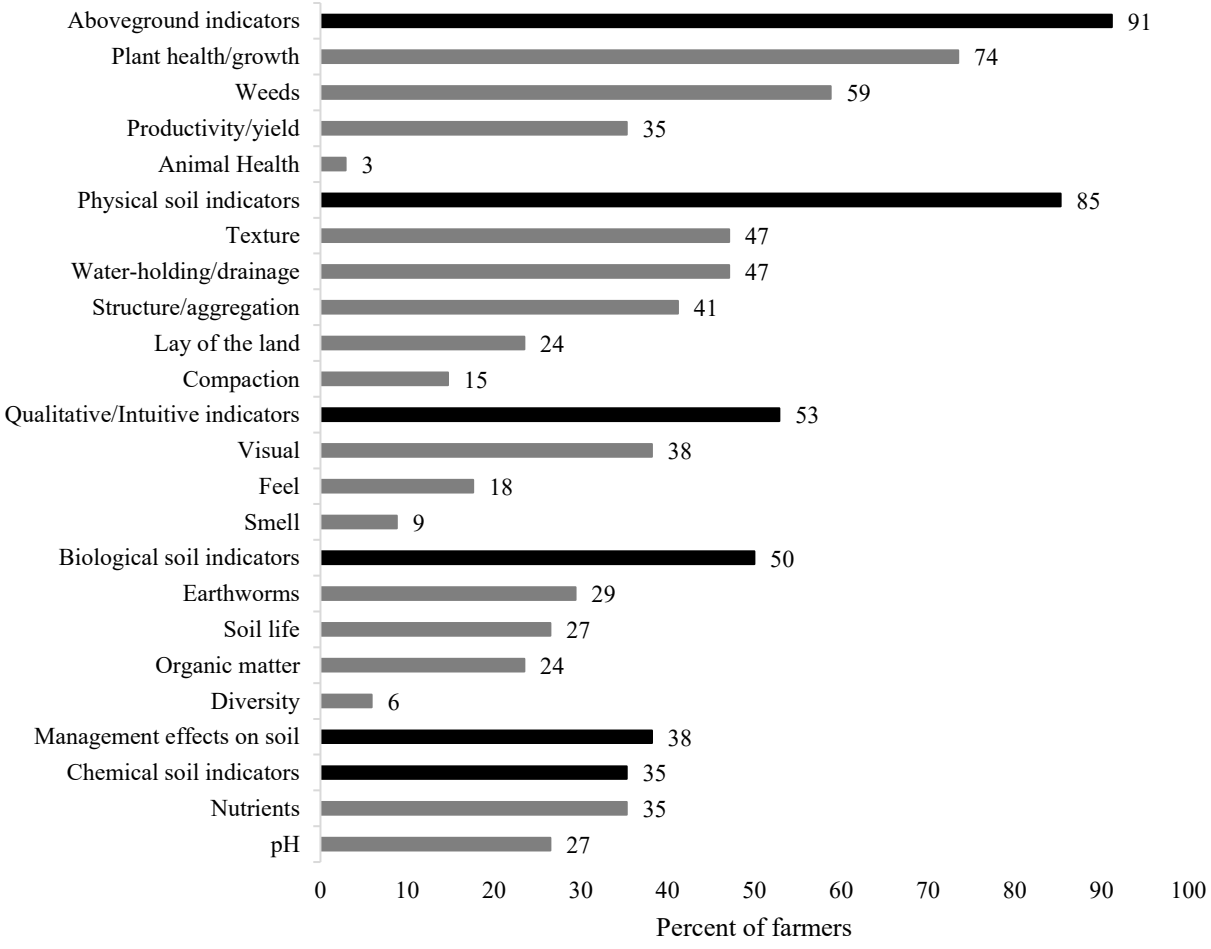


Figure 13. Most common indicators used by 34 Maritime farmers to assess soils. Black bars indicate major themes, and grey bars indicate specific categories within themes.

Many farmers acknowledged the impact of management decisions on soil: "…there's no such thing as a bad soil, just badly managed soil" (Farmer NB09). Farmers pointed to management decisions like tillage, N-inputs, organic matter additions, cover cropping and length of rotation as affecting soil health. Some farmers drew direct links between their management practices and the health of their soils:

> "… knowing what we know of the history, there definitely seems to be a correlation between longer rotation, generally keeping most of the green matter in the field, having proper rotations - there's definitely a trend that those are generally better performing fields, and I also believe them to be stronger microbially, better organics and breaks some of the pest cycles that you might see otherwise in shorter rotations." (Farmer PE13).

Physical soil indicators were mentioned more frequently than either biological or chemical measures (85%). Physical indicators could be divided into three main categories: texture, structure/aggregation, and drainage/water-holding-related indicators. Approximately half (47%) of farmers mentioned using texture to assess soil, and most preferred sandy or silty soils over clay soils. Farmers used words such as 'loamy', 'light', 'friable' and 'soft' to describe their ideal soil texture. Many farmers also discussed the importance of aggregation and 'crumb' for aeration, water infiltration, water holding, drainage and to withstand erosion. Drainage issues seem to be particularly important for Maritime farmers, citing high rainfall levels as a key factor in their preference for sandier soils, better aggregation and tile-drained fields.

Biological aspects were discussed by 50% of farmers, including earthworms (29%), soil life (26%) and organic matter (24%). Two farmers mentioned the importance of species

diversity for soil: “soil’s like an ecosystem of its own and a habitat for lots of things, so if it seems like there’s not a diversity of species … that would make us feel like it wasn’t a healthy soil.” (Farmer NS03). Chemical indicators were mentioned least often (35% of farmers), and farmers also tended to spend less time discussing chemical indicators than physical or biological; most farmers mentioned nutrients, fertility, or pH only in passing. Only three farmers (9%) mentioned a combination of physical, chemical and biological soil attributes.

Many farmers’ assessments came from qualitative or intuitive judgments. Visual soil assessment was used by 38% of farmers, whether to assess colour, aggregation, earthworm presence or just by intuitive judgment. For example:

> “we can also, just from years of experience, often look at a soil and look at things like the state of aggregation, the amount of crop residue and so forth that we see mixed in with it and that also gives us an idea. I've noticed that … if I'm tilling a bed [that's] coming right out of a cover crop, especially one of our year-long cover crops, just looking at the tilled soil behind the tractor you can see a visual difference between that soil and a soil that's been cropped more intensively over a period of time.” (Farmer NS11).

In this way, the farmer is combining knowledge of the management practices with visual inspection and years of observation for comparison. Some farmers also used the soil’s feel to assess texture or structure, and three farmers mentioned a ‘pleasant’ or ‘earthy’ smell as being important.

Although a few farmers’ answers were very simple – three farmers relied solely on productivity as a soil indicator – most farmers acknowledged soils’ complexity. Several

farmers mentioned freely that they did not know what made a soil good or bad; as one farmer put it,

> "I think we're limited right now in our knowledge of what is good and what's bad… so at this point we have to kind of be part anecdotal about it … for the most part it's observations that we make on farm with a little bit of laboratory data behind it, but we're thirsty for more." (Farmer PE06).

Another farmer mentioned the 'rabbit hole' that is soil science: "There's a lot of things about soil - drainage, all the fertility, level of pH - so the more you learn, the more complicated what defines good soil and bad soil is" (Farmer NB09).

4.2.3. Question 2: If we were to walk out to a piece of land right now and look at the soil, what specific things would you look for or think about when trying to assess it?

The purpose of this question was to explore, in more concrete terms, how farmers conduct in-field soil assessments. Again, the most important factors were health and vigour of the plant life, or the type of weeds present, and farmers discussed how they would assess plant health and weed presence as indicators of soil health. Farmers were more specific about how weeds could be indicators of soil health: pH (moss, wild strawberry, bedstraw); water-logging (soft rush, water avens, buttercup); compaction (plantain). Certain weeds were also associated with nitrogen levels, although there was some discrepancy between farmers' assessments: one farmer considered lamb's quarters to represent better fertility levels than grasses, whereas others considered grasses to require higher fertility than other weed types. Dairy farmers tended to view weed presence as a general indicator of poor soils.

Again, physical soil aspects followed above-ground indicators in importance (Figure 13). Water-holding, drainage, texture and structure were widely acknowledged as important factors to assess. Two additional physical assessments were raised here: soil compaction and slope or lay of the land. Slope was particularly important, mentioned by eight (24%) of farmers and linked specifically with natural drainage, water-ponding, erosion (primarily water, but also wind), and topsoil depth.

Asking farmers how they would assess a piece of land led them to consider the goals or intended use of the soil in a way that was not addressed in the first question. Farmers noted that they would specifically look for soils that would help them grow their crop in question. As one farmer put it, when discussing how she and her partner had decided to buy their current piece of land, "We definitely didn't, for us, want a soil that would be too heavy, although we don't think that means that it's a bad soil in general, it just wasn't a good soil for our purposes." (Farmer NS03).

4.2.4. Question 3: Have you ever made a management decision because you wanted to improve your soil and if so, what was the decision?

All but two farmers made decisions with the specific goal of improving their soils. Seven farmers (21%) from a range of conventional and organic backgrounds said that they felt soil management decisions were constantly being made on the farm. Dairy farmers seemed to interpret the question differently than other types of farmers, often relating the question of soil management directly to pasture management. When asked about soil management decisions, farmer NB02 summed up the overlap well: "Management decision, like as to whether to drop the plows in it?" Soil management decisions were related to forage

or hay quality and yield, and the related impact that soil decisions may have on that, including rotation length (frequency of plowing/reseeding), pH management and fertility additions.

Cropping changes were the top soil management decision, including the use of cover crops or green manures, changes to the crop rotation or to the main crop, and increasing plant diversity both in the field (intercropping/pasture diversity) and in field margins (e.g. living mulches in pathways) (Figure 14). Cover cropping was mentioned by 44% of farmers as a key soil management decision, the single biggest cropping decision made by farmers to improve their soil. Many farmers took cover cropping for granted, mentioning the practice only in passing on to other more interesting decisions they had made; when they did go into more detail, farmers mentioned using buckwheat, oats, peas, clover, brown mustard, tillage radish and ryegrass as green manures for various purposes.

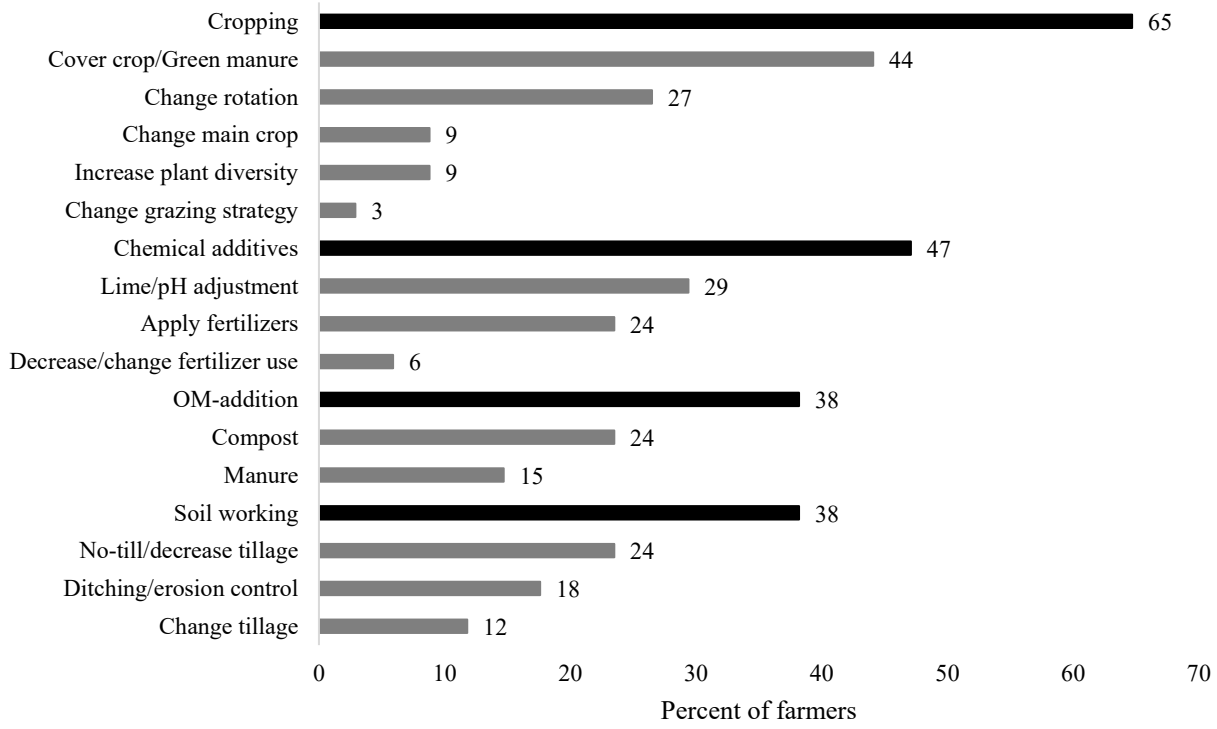


Figure 14. Management decisions made by 34 Maritime farmers to improve their soils. Black bars indicate major themes, and grey bars indicate specific categories within themes.

For dairy farmers, cropping changes often related specifically to reseeding their hay fields:

> "That's the biggest problem probably around here, people keep rotations too long, like continuous corn - one guy over here's got continuous corn for 16 years in the same field. They don't rotate, they don't re-seed, so they'll have a sod field for 40 years and even if they keep the pH right, you know, you get that bump from having a real crop" (Farmer NB06).

Dairy farmers also discussed trying to incorporate higher diversity into their forages, especially including N-fixing plants like clover and other legumes. Crop rotation was also a concern for vegetable and field crop growers, including cover crops, main crop rotation and, in a few cases, choosing to change their main crop out of soil considerations.

Adjustment of pH as a soil improvement consideration was mostly restricted to dairy farmers, although it was also mentioned by one field crop and one organic vegetable farmer. The choice to apply synthetic fertilizers as a soil amendment was spread between farm types, with farmers ranging from conventional dairy to organic vegetable and field crops. A minority of farmers (one conventional dairy and one organic vegetable) discussed their choice to stop or limit fertilizer use, although academic research remains inconclusive on the topic. For example: "I read about [what] nitrogen fertilizer does to soil ... too much nitrogen fertilizer just eats up the organic matter in your soil, so you're defeating the purpose by spreading nitrogen fertilizer sometimes" (Conventional Dairy Farmer, NB09). The organic vegetable

farmer mentioned the choice to rely on organic fertilizers to reduce harmful effects on the soil.

Changes to how the farmers work their soil was another major decision (38%). Three farmers had switched to no-till (one field crop and two dairy farmers), and four organic vegetable farmers mentioned reducing their tillage. Others discussed changes to their tillage practices: for organic vegetable farmers, this meant implementing a permanent bed system or choosing less-impactful machinery; one dairy farmer decided to plow cross-slope to reduce erosion. Other decisions to reduce erosion included changes to ditch patterns and using soil coverage – whether cover cropping or tarps, plastic or mulch, in the case of smaller-scale vegetable farms – to reduce winter erosion. Organic matter additions were mentioned just as often as tillage changes, and by the full range of farm types. These OM additions included manure, compost, and increasing cover crop density to increase total biomass return.

Several farmers mentioned the importance of their professional and personal network for decision-making. Two farmers relied on agronomists or professionals to help them interpret their soil test information. Others discussed the importance of attending conferences, talking with relatives or other farmers, or reading online to help decision-making. Three farmers also mentioned the financial considerations of making soil management decisions, whether the cost of inputs or the need to balance the perceived benefits of positive soil management decisions with the perceived costs in productivity: "…we still need more information before we can be more confident that … taking another cash crop out of the rotation is actually going to improve soil productivity, because if it doesn't you may be putting yourself at a loss for no reason." (Farmer PE06). Others mentioned time constraints, for example, not being able to seed a cover crop after a full-season crop.

4.2.5. Questions 4 & 5: Do you ever conduct soil testing on your farm? How do you use the soil test information?

Twenty-five farmers (74%) indicated that they regularly conducted soil testing on their farm, and a further 8 farmers (24%) said that they did conduct soil testing, but not regularly or recently. Only one farmer, an organic vegetable farmer, had never conducted soil testing.

Soil test information was primarily used to make nutrient and pH decisions, including the type and amount of fertilizer to add, manure or compost application, and lime application (Figure 15). Seven farmers mentioned tracking micronutrients as well, including boron, sulphur, magnesium, zinc, copper and calcium. Three farmers tracked organic matter, two of whom were organic, and a further three farmers mentioned tracking cation exchange capacity. One farmer, an organic vegetable grower, used base saturation to "balance" their soil, according to methods developed by W. Albrecht (Albrecht, 1975). Three farmers also mentioned the importance of ongoing soil testing "to use as a benchmark and a guideline to see over time whether or not you're going in the right direction." (Farmer PE13).

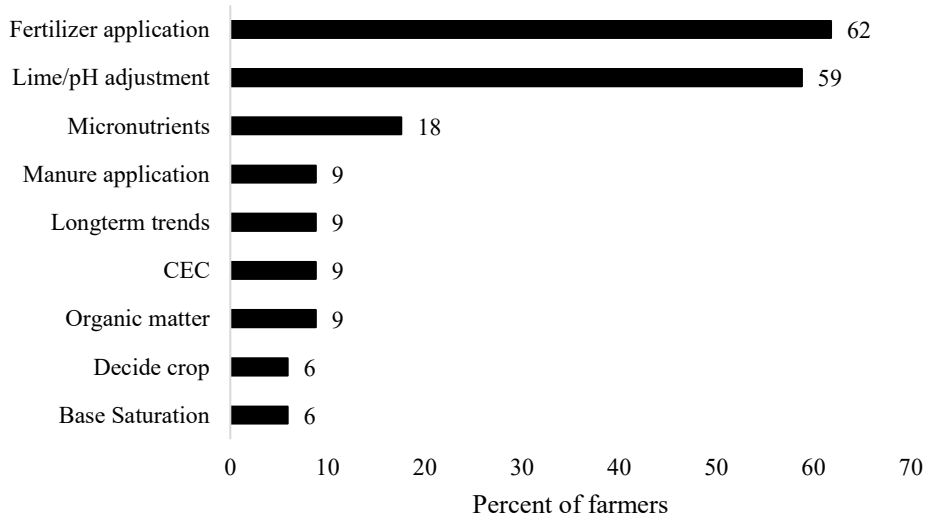


Figure 15. Ways in which 34 Maritime farmers use their soil test information to inform their decision-making.

Although several conventional farmers were critical of the standard soil test, they were generally more open to following recommendations and relying on the soil test to make management decisions than organic farmers. Seven farmers mentioned not understanding or using their soil test information at all, five of whom were organic. The sentiment that soil testing was not appropriate for organic farms was expressed by six farmers, for several reasons: they do not use chemical fertilizers, preferring "subtle" changes over quick fixes; it does not fit with their farming ideology; it lacks a holistic feel; they thought that the recommendations were too high and wanted to be "safe"; and they felt a lack of support and a lack of resources for organic farmers to interpret soil tests and improve their soils. One farmer summed up the feeling well:

> "I think most soil tests are geared towards conventional farmers, especially with the recommendations they make as far as how many pounds of nitrogen you need to bring in, and so since we're not bringing in any chemical fertilizer, our main fertility source is compost that we make on farm… understanding how to interpret soil tests is still a big challenge… [but] the bigger challenge is what to do with the information I get once I get it, and kind of filtering it through my own personal way of farming and wanting it to feel right for our farm." (Farmer PE05).

4.2.6. Questions 6 & 7: Have you ever heard or read about the term "soil health"? How would you define soil health?

Only three farmers had never heard of soil health, two of whom were conventional dairy, and one organic field crops. Like academic definitions of soil health, farmers' definitions varied widely. Of the 31 farmers who had heard of soil health, soil biology was the overriding theme: 27 farmers (87%) included some aspect of soil life in their soil health

definition (Figure 16). Aspects of soil biology that were mentioned included the soil ecosystem, insects, microbes (bacteria and fungi), OM, healthy plants, earthworms, biological activity/richness, absence of disease, and diversity of soil life. Chemical and physical aspects were mentioned less frequently, by 16 farmers (52%) and 17 farmers (55%) respectively. Eleven farmers (35%) included aspects of all three in their response, and a further ten farmers (32%) mentioned two of the three. Pearson's correlation revealed that older farmers were less likely to speak of chemical aspects of soil health (age and chemical indicators: r = -0.39, p=0.028), and were marginally though non-significantly less likely to combine chemical, physical and biological indicators (r = -0.29, p=0.12).

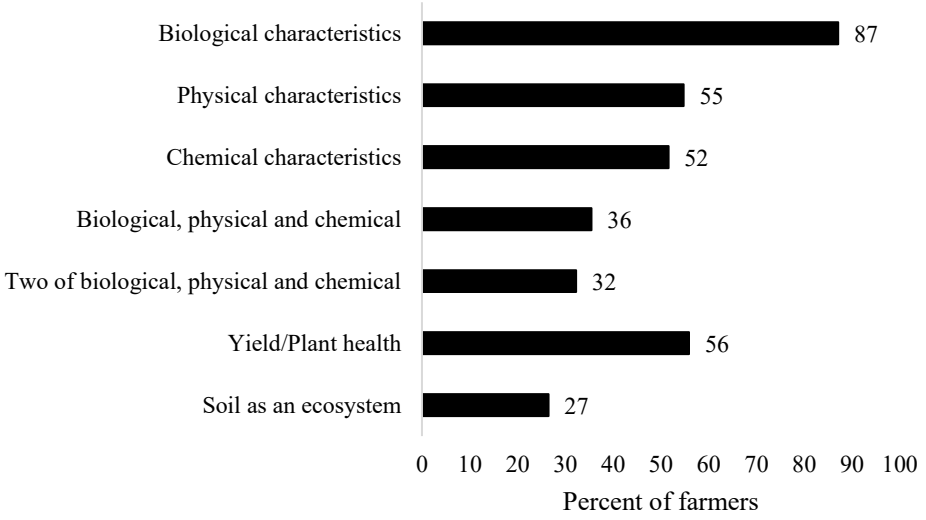


Figure 16. Major themes discussed by farmers in their soil health definitions.

Farmers' soil health definitions were largely rooted in their perspective as producers. Approximately half (56%) of farmers saw yield or plant health as primary goals of soil health: "Healthy soil grows healthy crops" (Farmer NB07); "I guess good soil health is, it's an environment that the plants can be the healthiest in" (Farmer NS07). Some farmers (27%)

talked about the soil as an ecosystem or organism itself, in the way that ecologists might speak of ecosystem health. For example, farmer NB05 defined soil health as "the whole ecosystem associated with the soil, from the insects to the plant species to the nutrients and the … whole circle of life associated with it." Three farmers acknowledged the multifunctional aspects of soil by talking about both good crops as well as ecosystem function. Nine farmers (29%) defined soil health in relation to the history of the land and the management practices in place. "To me soil health is a field that has not been worked too hard in its life, whether it be the right nutrients put back into it, whether it be lime, fertilizer, rotation, organic matter… you don't want your land to get tired. You get tired, you're not going to produce. If your land's going to get tired, it's not going to produce." (Farmer PE10).

Farmers' soil health definitions were overwhelmingly reductionist (Kibblewhite et al., 2008): 25 farmers' definitions focused explicitly on biological, physical or chemical soil attributes, while six farmers' definitions could be considered integrated or conceptual, all of whom were organic. Pearson's correlation showed that younger farmers were slightly more likely to give a holistic definition of soil health than older farmers (age and holistic definition: $r = -0.25$, $p=0.18$). For these farmers, soil itself was alive; soil was both relatable and comparable to human health, and was recognized holistically beyond human-based goals. The idea of the soil as an organism was brought up several times: "soil health … it's a living organism, so to speak" (Farmer NS09). Another farmer talked about "the idea of soil being actually alive and being a functioning system, similar to somebody's gut" (Farmer PE06). One organic vegetable farmer talked about the importance of soil for many species:

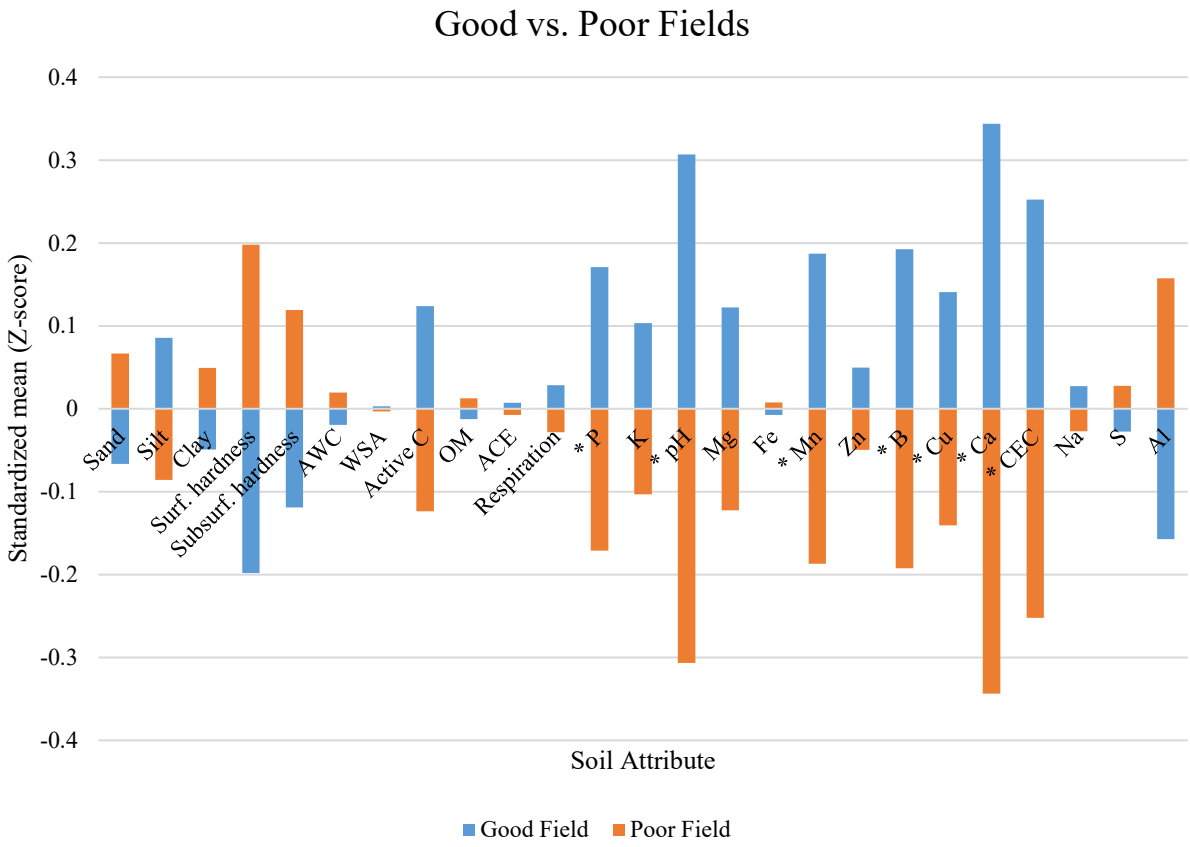
> "to me I guess the word seems more like how it would relate to a huge diversity of species, not just one species of *Homo sapiens* … because a lot of times [when] people

talk about soil, it relates a lot to how it can affect us as humans, but I don't really think that that is what soil health means to me." (Farmer NS03).

4.3. Soil Test Results

Soil results were described in more detail in Chapter 2. Soil indicator values ranged widely, and overall CSHA scores ranged between 31 and 77. On average, the fields scored best for potassium levels (85) and for available water capacity (81). The lowest average scores were for phosphorus: only four of the 68 fields had 'ideal' phosphorus levels, a further five fields were considered acceptable, and the remaining majority had exceedingly high levels. Surface hardness also generally scored very low, at an average of 25, likely because of drought at the time of sampling. Micronutrients scores were also low because of naturally high iron levels.

Paired t-tests revealed that farmer-selected good soils were rated higher than poor soils by the farmers' scorecard ($p<0.001$) but not by the CSHA ($p=0.110$; average good score=55.9, average poor score=52.6). Only three CSHA indicators were significantly different between good and poor soils: pH ($p=0.01$; average good pH=6.3, average poor pH=5.9), P ($p=0.03$, average good P=141.9, average poor P=110.7), and Mn ($p=0.045$, average good Mn=68.5, average poor Mn=56.3) (Table 3, Chapter 2). There were additional significant differences in other chemical indicators between good and poor fields, including B, Cu, Ca and CEC, as shown in Figure 17.



* significant difference between good and poor soils at p=0.05

Figure 17. Differences between good and poor fields by soil attribute.

The results from the PEI provincial laboratory (Appendix A) reveal several further differences between good and poor fields. Boron was significantly higher on good soils (p=0.038; average good B=0.8, average poor B=0.6), as was Cu (p=0.049; average good Cu=2.7, average poor Cu=2.0), Ca (p=0.003; average good Ca=1690.0, average poor Ca=1220.7), buffer pH (p=0.006; average good buffer pH=7.1, average poor buffer pH=6.9) and CEC (p=0.025; average good CEC=12.1, average poor CEC=9.9).

4.4. Farmers' In-Field Soil Health Assessment

Chi-square test for association in Minitab 17 was used to compare the farmers' scorecards to the actual test values, with H_o: farmers' rating and actual results were independent, and H_a: farmers' rating & actual results were dependent. Compaction was not included, as originally planned, because drought during the sample period affected the accuracy of the test values. Because both farmers and the soil test were less likely to give a rating of "0", this sometimes resulted in expected cell values of less than one, violating the assumption that all expected cell values should be greater than one. To combat this, the "0" rating option was sometimes excluded from the analysis, resulting in a slightly smaller sample size.

Table 8. Chi-square test for association comparing farmers' soil assessment to CSHA soil assessment.

	Q7 vs. AWC[a]	Q8 vs. WSA[b]	Q9 vs. P & K	Q10 vs. micronutrients	Q11 vs. pH	Q12 vs. OM[c]	Q16 vs. respiration
Sample size	66	52	68	56	67	67	58
Percent agreement	52	43	44	62	57	60	54
Pearson X^2	7.707	1.458	20.896	7.791	13.347	5.338	6.924
DF	2	2	2	1	4	2	2
p-value	0.021*	0.482	<0.001**	0.005**	0.010*	0.069	0.031*

*significant at α=0.05
**significant at α=0.01
[a] AWC = available water capacity
[b] WSA = water-stable aggregates
[c] OM = organic matter

Table 8 shows the results of the chi-square test. Macronutrients (P&K, $p<0.001$) and micronutrients ($p=0.005$) were the most significant in their rejection of H_o, indicating that farmers' assessments agreed with the CSHA assessments for these categories. Farmers' assessments also agreed with CSHA AWC ($p=0.021$), pH ($p=0.01$) and respiration/biological activity ($p=0.031$). Farmers did not agree with CSHA assessments of WSA ($p=0.482$) and moderately agreed with OM assessments, although not significantly ($p=0.069$).

The relationship between farmers' assessment and soil test results is depicted in more detail in Figures 18 A-G. In general, the CSHA tended to overestimate soil properties compared to the farmers' assessments. Figure 18A shows that when farmers' scores did not agree with the CSHA scores, farmers were more likely to give a lower AWC score than the CSHA. A similar trend was seen for P and K levels (18C), micronutrient levels (18D), OM (18F) and biological activity (18G), all of which the CSHA was more likely to overestimate than underestimate. This pattern is not seen for estimates of WSA, where the CSHA was as likely to overestimate as to underestimate, as shown in Fig. 18B.

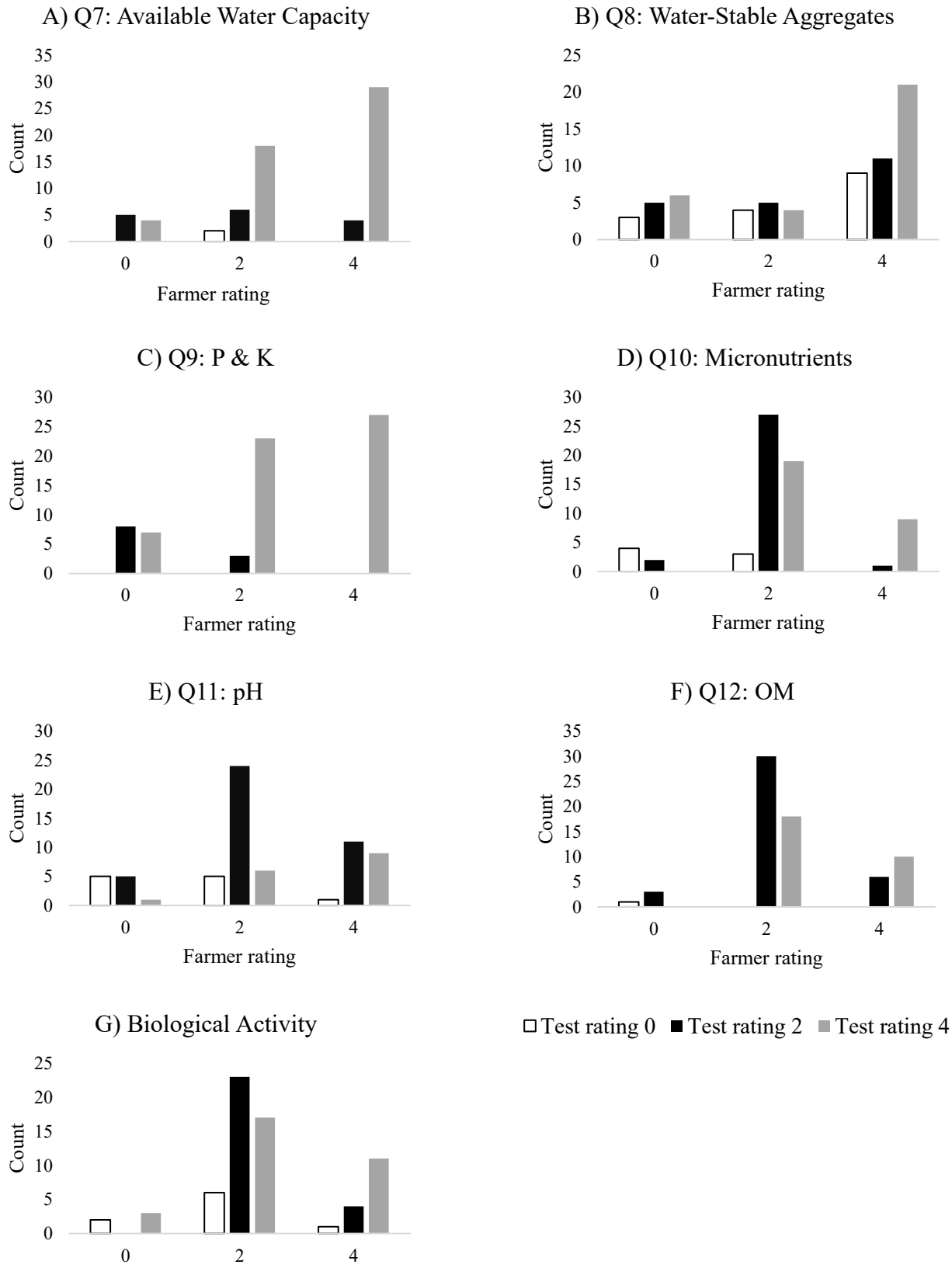


Figure 18 A-G. Farmers' soil ratings versus soil test ratings. Farmers rated soil properties as low (0), medium (2), or high (4), and farmers ratings were compared to low (0), medium (2) and high (4) ratings for soil test properties based on CSHA scores.

4.5. Follow-up Farmer Interview

Follow-up interviews were conducted by phone between February 27 and April 18, 2017. Twenty-seven of the thirty-four original farmers participated in the follow-up interview process. Several farmers were away on vacation for the winter; others did not respond to requests for an interview.

4.5.1. Farmer Surprise

Farmers were most surprised by the high levels of compaction in their fields; unfortunately, many of these values were likely inaccurate because the dry soils negatively affected the reading, an issue which was discussed with farmers during the interview (Figure 19).

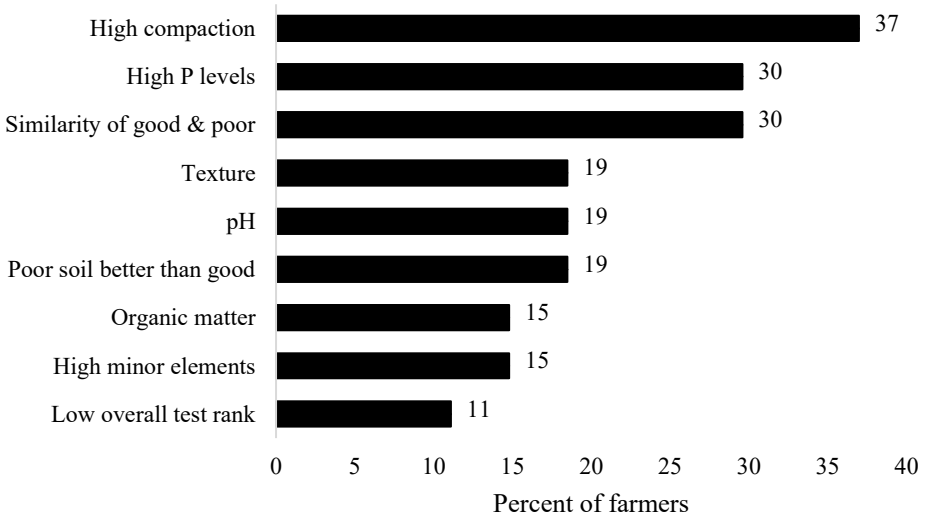


Figure 19. Soil test results that were surprising to farmers.

The second most common surprises were the high levels of soil phosphorus and the little or no difference in CSHA results between 'good' and 'poor' fields (30% each).

Evidently many farmers expected the soil test to show bigger differences between the two fields; on 10 farms, 'poor' fields were even ranked higher than the 'good' per the CSHA, which was a surprise for those farmers. Some farmers found this discrepancy frustrating because they could see clear differences between yield or crop health in the two fields that was not reflected in the CSHA:

> "… the crop over here [on the poor field] was definitely, well, I'd say a poor crop, a poor crop versus the other one on the good field was actually a fairly good crop. So, that was surprising to see that there wasn't much of a difference between the two fields in terms of the soil test." (Farmer NS01).

One of these farmers disagreed with the results on that basis, and therefore was unimpressed by the CSHA. Other farmers could make sense of the test results and reason that perhaps other fields that were farther apart or that had seen more significantly different management practices may have shown larger differences.

The high phosphorus levels were particularly distressing for many farmers, even though presumably farmers would have seen these numbers before on their provincial soil test results. Perhaps the ranking system that shows low scores highlighted in red strongly emphasized this point in a way that the provincial test does not. Similarly, pH and OM levels were surprising for 19% and 15% farmers respectfully, even though presumably they would have had some idea of these levels.

The texture of their soils was surprising for 19% of farmers; most of these farmers had expected higher levels of clay, which seemed to be a common myth across the Maritimes and was even brought up by one farmer: "That's something that should be kind of yelled loud and

clear because everybody seems to - I don't know about people you've talked to - but everybody seems to think they have high clay soil, that I've talked to." (Farmer NB06). The highest clay content in this study was 17.8%, which was still considered a medium-textured soil.

4.5.2. Farmer questions and confusions

Most farmers' questions revolved around how the CSHA ranking system worked (48%) (Figure 20). The second most common question topic was on the chemical test values, including questions about the provincial soil test. Many of these questions revolved around phosphorus levels: what caused high levels; what an ideal level would be; what management practices would help reduce P-levels. Farmers were also concerned about Mn, Fe and Mg, and several were unsure about what an ideal pH would be. With respect to the standard soil fertility results within the CSHA, farmers asked about Ca, S, B, Al, lime index, cation exchange capacity and base saturation.

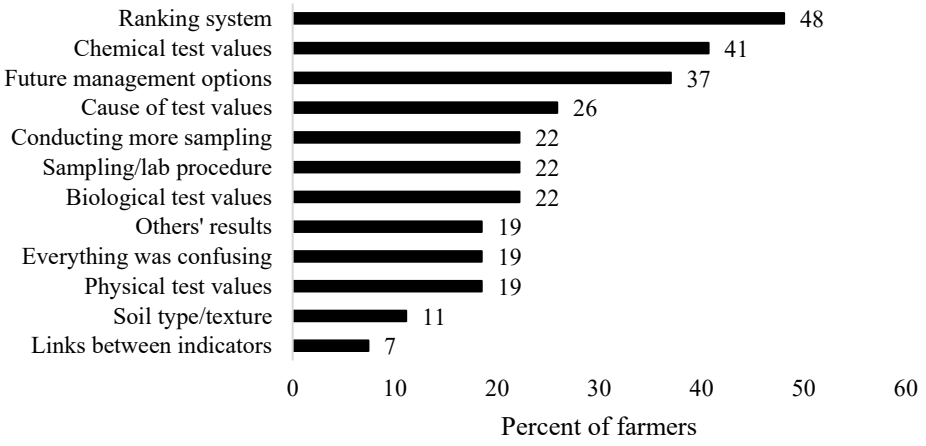


Figure 20. Questions asked by farmers about their soil test results.

Many farmers (37%) asked about future management options for addressing the problem areas on their test, and 26% asked about the causes of specific test values. Again, many of these questions were related to high P and to addressing pH. A minority of people also asked about improving biological numbers, about addressing the minor elements, and about addressing physical factors such as aggregation and compaction. Farmers also had questions about the biological test values (22%), most of which were related to the ACE protein test, and several regarding respiration and active carbon. Some farmers (19%) found the entire CSHA test to be quite baffling.

Many farmers were interested in the lab and sampling procedures used in the test, and 22% of farmers were interested in conducting more soil testing, with associated questions about how to do so. Farmers were also interested in others' results and their comparison to other farms (19%). A minority of farmers asked questions about the links between different indicators (7.4%).

4.5.3. Changes to management based on CSHA results

Based on the CSHA scoring system, only the highest scoring field, NB02G, could reasonably be considered to require no management intervention, because it scored high on all indicators except for surface and subsurface hardness and micronutrients, the former being adversely impacted by weather at the time of sampling, and the latter being impacted by naturally occurring iron levels. Of those interviewed, 74% said that they would undertake some changes in their management in response to their soil test results, 15% did not plan to make any changes, and 11% were unsure. The average CSHA score was 50 for those who did not plan to change their management and 56 for those who did plan to change, not a

significant difference, although every farmer with high scores planned to change in some way. Perhaps these high-scoring farmers were intentionally working to improve their soils, and were more interested in continuing to improve than lower-scoring farmers.

The most common changes were to address the P issue and to increase organic matter; farmers also talked about adjusting pH and addressing compaction in their fields. Many farmers were not specific about the changes they hoped to make, but said that the testing would certainly inform their decision-making. Still, although high P was a problem for 26 of the 27 farmers who participated in the follow-up interviews, only seven farmers discussed their intention to reduce those levels.

4.5.4. Usefulness of the CSHA

Most farmers (71%) found the CSHA to be useful and would like this kind of testing to be commercially available; a further 11% did not find the testing useful, and 15% did not know if the test was useful or not. Almost all organic farmers (92%) found the CSHA useful whereas only 54% of conventional farmers did. Most who said "yes" cited the importance of being able to see the biological side of their soils: "… it's something that we always talk about, every time you go to these [soil health] meetings, it's like, 'oh, the life of your soil', but … I've never had a way to kind of look at it, or measure it, or know what's going on." (Farmer PE08).

Of the seven farmers who said it was not useful or that they were unsure, most said that they did not fully understand the test and therefore would not use it or could not tell if it was useful. "Some of this doesn't mean a whole lot to me at this point. Now maybe if I read up on it maybe it would. But I guess right now I don't think I'm educated enough to tell you

that I would know what to do with that." (Farmer NS06). One farmer who disagreed with the test results was not in favour of the test at the time, but thought that it could be more useful if the ranking system were better suited to Maritimes soils. Another mentioned that the CSHA should be compared to yield results to see if the CSHA was useful or to change the ranking system.

In this vein, several farmers discussed the challenges associated with this kind of testing: the complexity and the high level of knowledge required for interpretation (22%); the cost of more in-depth testing (15%); and time constraints for sampling (11%). Farmers said that the test would have to be affordable for them to take advantage of it, and some suggested subsidizing the cost of the testing. To help with interpretation of the results, five farmers suggested that some management recommendations should be included directly on the test to help the farmer develop a plan for improving their scores. One farmer also recommended that an explanation of the ranking system would be useful, for example, by including the scoring curves directly on the soil test.

5. Discussion

5.1. Farmers' Soil Health Perceptions and Assessments

The first objective of this chapter was to characterize farmers' perceptions of soil health and understand how farmers assess their own soils. The online survey identified 73 different indicators (Appendix F) used by farmers across the Maritimes, with an average of 6 indicators per farmer. In the interviews, the most commonly used indicators were aboveground indicators such as plant health, weed presence or yield, and physical indicators such as texture or water-

holding capacity (Figure 13). Almost all farmers (94%) had made some management decisions to improve their soils, most notably cropping changes including cover cropping (Figure 14). All but one farmer conducted soil testing, and 74% conducted soil testing regularly on their farm; soil test results were primarily used to make decisions about nutrients and pH (Figure 15). Almost everyone (91%) had heard of soil health, and farmers' soil health definitions focused overwhelmingly on biological aspects of the soil and on the production side of soil health – plant health and productivity – while a minority of farmers mentioned environmental or ecological roles of soil (

Figure ***16***). Further, about one-third of farmers specifically defined soil health as a function of management history. These results confirm Hypothesis 2.1, showing that farmers' perceptions and definitions of soil health were rooted in their position as an agricultural producer and related to their goals for the farm.

Hypothesis 2.2 was also confirmed, as differences in soil health perceptions between farm types and demographics were noticeable in several responses. Organic farmers tended to be more critical of the standard soil fertility test results than conventional farmers, were generally more welcoming to a diversity of weeds, and were more likely to give a holistic definition of soil health. In the follow-up interview, organic farmers viewed the CSHA as useful at a higher rate than conventional farmers, which is in line with findings from Lobry de Bruyn & Andrews (2016) who found that farmers who employ conservation strategies on-farm are more likely to support in-depth soil testing. Dairy farmers were another unique group: they tended to view weeds as a negative indicator of soil health, and seemed to link the question of soil management directly with pasture management and forage yield/quality. Dairy farmers also emphasized the importance of pH more than other types of farmers.

Carlisle (2016) highlighted three demographic features that affect farmers' soil health perceptions: age, gender and education. We did not collect information on the farmers' education levels in this study. Gender is also difficult to assess here because all but one of the female farmers were organic farmers, which may confound the results. However, if organic management could be considered an indication of positive feelings towards conservation, this correlation supports findings that women tend to hold more positive views about conservation practices (Carlisle, 2016). Younger farmers were marginally more likely to include chemical indicators in their soil health definitions and to combine chemical, physical and biological indicators, as well as to give more holistic soil health definitions.

Examining farmers' definitions through the lens of Kibblewhite et al. (2008) shows that most farmers' definitions were reductionist, and a minority of farmers' definitions were integrated. These integrated definitions were all given by organic farmers, who discussed holistically the life of the soil itself and the importance of soil beyond human ends.

These findings corroborate the work of Lobry de Bruyn & Abbey (2003), in that farmers used crop health as a major indicator in their soil assessments, soil health definitions were typically qualitative rather than quantitative, and productivity/crop health took precedence over environmental concerns. In comparison to the soil health definition put forward by Doran et al. (1996), farmers' definitions leaned heavily on the topic of biological productivity and plant health, and often ignored the wider applicability to environmental issues. Failure to draw links between soil health and ecological data – in short, by focusing too heavily on productivity – may limit the applicability of soil health to broader public benefits, both agricultural and non-agricultural (Bennett et al., 2010). Soil scientists should

begin to introduce the idea of soil health for environmental concerns, keeping in mind farmers' perspectives and needs, and listening and responding to farmers' ideas and concerns.

Worldwide, farmers use 90-100 indicators to assess their soils (Kelly et al., 2009), although an individual farmer typically relies on 3-6 (Lobry de Bruyn & Abbey, 2003). The indicators mentioned in this study ranged through biological, physical and chemical aspects, as well as several management-based indicators. This is unique from most scientific judgments of soil; while soil scientists would likely consider field history, it would be in relation to the impact on soil attributes rather than an indicator of the soil's condition. These differences in viewpoints emphasize the practical, management-based perspective of most farmers.

Farmers' emphasis on aboveground indicators such as plant health, weeds, yield and animal health echoes the findings of Romig et al. (1995) who showed that farmers' assessments expanded beyond soil-based indicators. These indicators, along with others such as visual, feel and smell indicators, show that much of farmers' soil knowledge is based on sensory observations (Romig et al., 1995). Chemical soil tests that reveal insights into fertility are one exception (Romig et al., 1995).

5.2. Comparing the Farmers' Scorecard to the CSHA Soil Health Assessment

The second objective for this chapter was to compare farmers' in-field soil health assessments to a laboratory soil health assessments. Hypothesis 3.1 was not confirmed, as the in-field scorecard differentiated strongly between good and poor soils whereas the CSHA overall score did not (p=0.110). There are several possible reasons for this discrepancy, most

related to the weaknesses of the CSHA scoring system outlined in Chapter 2. First, the CSHA is not calibrated to yield data, whereas aboveground indicators such as plant health and yield are important factors in farmers' soil assessments. The only CSHA factors that differentiated good from poor soils were pH, P and Mn. From the farmers' perspective, low pH might contribute to a lower score on several scorecard indicators, such as nutrient availability and crop health, which would compound the perceived differences. The CSHA scoring system is also not calibrated to this region, and others have noted that the CSHA can be made more sensitive by weighting indicators based on PCA (Congreves et al., 2015). A similar method could be employed in the Maritimes. Finally, because there is no regional database, CSHA scores may not have been scaled ideally by texture groupings – in fact, there were no fine-textured soils in this study, which highlights the potential need to create new textural categories that better reflect the actual texture of Maritimes soils. Finally, soil fertility recommendations are not Atlantic or regional rankings, but vary by province, which could affect the relationship between farmers' perceptions and CSHA results between provinces.

The inclusion of pH and nutrient values as soil health indicators was raised as a concern by farmers at a recent soil health discussion group in PEI (PEICOPC, March 2017). Because these factors can be changed by spreading lime or fertilizer, several producers saw this as a "band-aid solution" for improving soil health scores. Generating a soil health score using only the physical and biological CSHA scores increased the average score by 3 (st. dev.=7), although many scores were lowered. However, the test was not better able to differentiate between good and poor fields with this new scoring system (p=0.36).

In a similar study in Kenya, Mairura et al. (2007) found that farmer-identified 'fertile' and 'infertile' soils were differentiated by pH, total organic carbon, CEC and available-N. It is

difficult to compare these results to Kenyan soils, not least because of the highly different farming system described by Mairura et al. (2007), however, there are some consistent findings. In the current study, good and poor soils were differentiated by pH, P, Mn, B, Cu, Ca, buffer pH and CEC. It is interesting that paired t-tests did not show that OM was significantly different between good and poor fields, nor were any other physical or biological indicators.

Hypothesis 2.2 was partially confirmed through the Chi-square analysis, in that farmers' assessments agreed with CSHA assessments of macro- and micro-nutrients, and were in lesser agreement with WSA test values, a less-commonly provided soil test for producers. However, the tests for which farmers' assessments were moderately in agreement (p <0.1) included pH, OM, AWC and biological activity, a group which includes both typical soil test information (pH and OM) along with physical and biological tests that farmers likely would not have seen before. Farmers' assessment of AWC could have been influenced by the regional drought during the sampling period; perhaps water-holding capacity was on farmers' minds at the time and was something that farmers had been assessing through crop appearance. Also, given farmers' emphasis of biological aspects of soil health, biological activity may be something that farmers assess in-field, for example, by looking for earthworms or other soil life. Because farmers develop an intuitive soil sense through years of observation (Romig et al., 1995), farmers may have an idea of these unique values.

Farmers emphasized soil biology over SOM throughout the interviews: only 9% of farmers used their provincial soil test to monitor OM; there was lower agreement between farmers and the CSHA on OM than on soil biology; and when discussing soil health, farmers emphasized soil life over OM, although soil biology is a subset of SOM and the two are

intimately connected. Perhaps farmers perceive the living fraction of SOM more readily because it can be assessed visually (i.e., presence of earthworms or insects), or because SOM feels more static or more difficult to relate with than soil life in general.

Liebig & Doran (1999) found that farmers' perceptions were accurate or near-accurate 75% of the time, and their perceptions were more accurate for good soils than poor soils. Unfortunately, because of the small sample size, it was not possible to compare differences between farmers' assessments on good and poor soils here because the analysis resulted in too many 0's for the Chi-square analysis. In their study, farmers' perceptions were less accurate for compaction, infiltration and water-holding capacity, which reflects the findings of the current work. Although farmers in their study were not very accurate at assessing macronutrient levels, they also tended to underestimate those values when they were wrong. Liebig & Doran (1999) concluded that consulting with the farmer on the state of their soils is a valuable way to begin point-scale soil assessments on-farm, and that farmer education would be a valuable way to improve their assessment in the weaker categories, conclusions that are echoed here.

5.2.1. Farmers' Responses to the Soil Health Analysis

Farmers were most surprised about high compaction, high P, and the similarity between their good and poor soils. Farmers expected the test to differentiate more between their two fields, and in some cases, were hoping for an explanation as to why their crops were healthier in one field than the other. Many (30%) were disappointed by the lack of differentiation, which caused some farmers to question the usefulness of the CSHA. Most confusions and questions revolved around the ranking system, the chemical test values and

future management options to improve their test scores. To make the results more useful, farmers suggested including management recommendations and an explanation of the ranking system to judge more clearly what actions to take, and how far their results needed to change to move from a "low" score to a "medium" score, for example.

Farmers' customary practices tend to override soil test information (Lobry de Bruyn & Andrews, 2016). This was reflected in farmers' responses during the follow-up interview: although most farmers (74%) planned to undertake some management changes after seeing the soil test results, some farmers were averse to change. This was especially evident for the issue of high P, where only 27% of farmers indicated their intention to reduce those levels. Several farmers indicated that they would need more testing before they would undertake management changes. Unwillingness to change may come from a poor understanding of test results, as most farmers who did not find the CSHA useful did not understand the results and therefore could not use it to make management changes. All farmers who scored high on the CSHA planned to make some management changes, whereas those with medium-low scores were less likely to make changes, possibly indicating a gradation in overall soil concern or soil knowledge. This reflects findings from Kelly et al. (2009), who recommended that all soil health indicators emphasize a practical application to make the soil test useful for on-farm decision-making. Using farmer-selected indicators can also help make the results more accessible to farmers (Lima et al., 2013).

5.3. Emphasis of Biological, Physical and Chemical Indicators

There are interesting differences between farmers' emphasis of biological, physical and chemical indicators depending on the question. When asked about their soil assessments, farmers emphasized physical indicators, perhaps because these types of indicators – like texture, aggregation or drainage – are readily assessable through in-field qualitative means. When defining "soil health", farmers discussed biological indicators most frequently, likely because "health" is something ascribed to living organisms. Finally, discussion around farmers' use of provincial soil tests focused on chemical indicators, because chemistry is generally the focus of provincial soil test information.

These differences indicate that farmers are generally aware of these "three pillars" of soil health, but do not necessarily link them under the concept of soil health. Given that farmers have considered their soils from these three angles, even under different contexts, it may be easier to introduce a multifaceted concept of soil health, especially if linked to areas of farmers' current understanding. The different areas of focus that arise when using the terms "soil assessment", "soil health", and "soil tests" re-emphasizes the importance of terminology and awareness of others' perceptions to minimize misunderstandings.

5.4. Weaknesses of the Current Work

Research in a variety of communities around the world has shown that farmer participation in research may be influenced by socioeconomic and historic factors such as income, community integration, settlement history, local knowledge, and environmental history, among others (Walters, Cadelina, Cardano & Visitacion, 1999). This study likely

attracted farmers who were already interested in soil issues or who were actively connected with farm-support organisations, which may over-emphasize soil health awareness and knowledge in the general farmer population. For example, 74% of farmers in this study reported regularly using soil testing, which may be higher than in the general farming population; work in the US corn belt indicated that only 30% of farmers there used soil testing, and that number is decreasing (Lobry de Bruyn & Andrews, 2016). The timing of the study likely also influenced the results, because interviews were conducted during the growing season when time constraints may have deterred some farmers from participating.

The CSHA scoring system may not be ideal for comparison with the farmer scorecard because it is not based on biological or environmental thresholds but rather on a database of regional farm results (Congreves et al., 2015; Moebius-Clune et al., 2016), which is not yet available in Atlantic Canada. The comparison of scorecard responses to CSHA test values could have been swayed by slight changes in the categories developed for comparison – for example, macronutrients and micronutrients were assessed by farmers qualitatively (i.e. "high" rather than at a specific level), and thus "high" for one farmer could mean something quite different for another farmer, and "high" on the CSHA may be something else entirely. Unfortunately, this issue was difficult to avoid given the complexity of soil interactions and the difficulty in asking farmers to identify specific levels, for example, nutrient levels in ppm. In addition, farmers were not blinded to the condition (i.e. good vs. bad soil), which may have influenced their scorecard soil assessments by exaggerating perceived differences between good and poor fields.

6. Conclusions and Recommendations

Farmers use a wide variety of indicators to assess soils on their farm, ranging from aboveground features to biological, chemical and physical indicators, as well as management-based and qualitative assessments. Farmers' soil health perceptions may differ from academic or scientific soil health discussions in their emphasis on biological components, plant health and productivity, with general lack of environmental considerations. Perceptions clearly differ between farm types, for example, organic farmers are more likely to think about environmental applications of soil health and to define soil health holistically. Highlighting these differences is useful for scientists when trying to educate Maritime farmers about soil health, as scientists may now choose to provide more information on the important role of soils for ecological considerations. However, scientists must recognize that farmers will fit the soil health concept into their own worldview and apply the concept in a way that is useful for them. Farmers' responses to the CSHA results show that if the soil health testing does not make sense within their needs, it will have no sway in their decision-making. Without applicability to farming, soil health will not form a useful basis for programs aimed at improving agricultural soils. Regional soil health programs will benefit from using soil health as a tool for two-way discussion, learning and decision-making that considers farmers' perspectives.

Chapter 4: Conclusion

1. *Folsomia candida* Growth as a Soil Health Indicator

1.1. Conclusion

Although growth of 1-day old *F. candida* neonates was significantly different between some substrates, this difference was largely split between two main groups and did not correlate with CSHA scores. Growth correlated positively with clay content and weakly with OM, and correlated negatively with pH, weakly so with sand and WSA. More significant differences were found by Nelson et al. (2011), where forest soils and composted manure were compared to agricultural soils in potato rotations. Considering that only mineral agricultural soils were used here, it seems that *F. candida* growth of 1-day old neonates may not be sensitive enough to smaller differences in soil health.

1.2. Recommendations

Given that the soils included in this study were all mineral agricultural soils, of medium to coarse texture, taken from Maritimes farms, it is possible that a wider range of soil types may have resulted in more noticeable *F. candida* growth changes. Further research could explore this question of sensitivity. However, given the time- and labour-intensive laboratory process and the fact that no tangible management guidelines can be developed from the test findings, the opportunities for using *F. candida* growth as a useful soil health test are limited.

2. CSHA and PLFA as Soil Health Indicators

2.1. Conclusion

Shifts in the PLFA profile were associated with CSHA indicators through PCA. WSA and soil respiration correlated with all PLFA microbial groups, notably AMF, gram negative bacteria, gram-negative stress indicator, and fungi; these correlated negatively with P, Cu, Al and the predator:prey ratio. Some of these changes in CSHA and PLFA indicators were linked to management changes. Perennial grass fields, followed by mixed fields, had higher respiration, WSA, fungi and AMF, and lower P. More intensively managed field types, such as undiversified grain and veg rotations, were higher in P and the PLFA predator:prey ratio and lower in respiration, WSA, fungi and AMF. Tillage and manure application were inversely related, with tillage correlated with P, Cu, Al, sand and the predator:prey ratio, and manure correlated with biological measures like soil respiration, AMF, gram negative bacteria, gram-negative stress indicator, fungi and WSA. Environmental factors, notably soil texture, also affected CSHA and PLFA indicators. Sand was inversely related to soil respiration, AMF, gram negative bacteria, gram-negative stress, fungi and WSA, but positively correlated with P, Cu, Al, and the predator:prey ratio.

2.2. Recommendations

Given the links between some CSHA indicators and PLFA microbial groups, it may be possible to use PLFA to explore more in-depth aspects of soil biology, both structural and functional, in concert with the CSHA's biological, physical and chemical components. The

strength of PLFA in rapidly screening the microbial community, exploring energy flows through the soil food web, determining bacterial:fungal ratios, measuring microbial biomass and assessing cell activity and cell stress make it a valuable tool. Future research that studies PLFA profiles alongside the CSHA may improve understanding of microbial structure and function as affected by a range of soil health indicators.

In addition, future work applying the CSHA in the Maritimes would benefit from making some specific changes to the test methods. In the laboratory, this includes: using Mehlich-3 extractions rather Morgan extractions for nutrient analyses; measuring OM on a combustion analyzer rather than through LOI; and altering soil respiration protocol so that samples are brought to a specific moisture content. A regional database should be created to improve CSHA scoring for the region by developing scoring curves specifically for Maritime soils. It is also recommended that thresholds for indicator scoring be based on production goals and environmental thresholds, such as by validating CSHA scores with yield data. Soil textural classes should be reassessed to better reflect Maritimes soils, and different micronutrients should be analysed to better reflect the natural occurrence of Fe and farmers' nutrient concerns. Finally, it would be beneficial to explore the development of a weighting system for individual indicators within the overall CSHA score, perhaps using PCA.

3. Maritimes Farmers' Perceptions and Assessments of Soil Health

3.1. Conclusion

Farmers use a wide variety of indicators to assess soil on their farm, the most common of which were aboveground indicators, such as plant health, and physical indicators including

texture and water-holding capacity. Most farmers were working to improve their soils, notably through changes to their crop rotation, and most conducted regular soil tests. Soil test information was primarily used for nutrient and pH decision-making. Almost all (91%) of farmers had heard of soil health, and farmers' definitions were dominated by biological soil indicators and a production-oriented viewpoint. These perceptions differed between farm types, however: organic farmers were more critical of provincial soil tests, viewed soil health more holistically, and found the CSHA more useful than conventional farmers.

3.2. Recommendations

Understanding how farmers' soil health perceptions differ from the views of soil scientists is important for developing effective soil health programs and cross-disciplinary soil health research projects. These insights will help reduce miscommunications based on previously unperceived differences in mindset. There are some key areas where farmers' understanding of soil health could be improved, notably an increased awareness of soil's multifunctionality and ecological roles. Soil health programs represent a unique opportunity to expand farmers' soil knowledge; however, it is equally important to note that by defining soil health in a way that is useful to their livelihood, farmers make sense of the term in their worldview and are probably more likely to apply the concepts in their daily management decisions. Because of the flexibility of the topic, soil health presents an excellent opportunity to integrate scientific knowledge with farmers' knowledge and create a reciprocal transfer of knowledge.

4. CSHA vs. Farmers' Scorecard

4.1. Conclusion

Although farmers' in-field soil assessments differentiated strongly between "good" and "poor" fields, this difference was not reflected in the CSHA scores. From the farmer interviews we established that aboveground indicators such as plant health and yield are important soil health indicators for farmers; however, the CSHA is not calibrated to yield data or any other biological threshold. This underlines the above recommendation to incorporate specific thresholds in the scoring system based on yield/plant health. Farmers' assessments agreed with CSHA assessments of macro- and micro-nutrients, and did not agree with WSA, a lesser-known soil test. Farmers' assessments moderately agreed with pH, OM, AWC and biological activity, showing that farmers can develop an intuitive sense of the soil even for soil attributes that had not been tested before.

Farmers were surprised to see that the CSHA did not differentiate between their good and poor fields, and for some, this reduced the usefulness of the test. Farmers suggested including management recommendations to improve their scores and an explanation of the ranking system with the test results. Most farmers said that they would undertake management changes in response to the test results, although some said that they would need more information before making changes. This largely resulted from farmers' lack of understanding of the test results.

4.2. Recommendations

Based on farmers' feedback, soil health programs in the Maritimes would benefit from being 1) easily understandable, 2) useful for farmers' needs, and 3) a reciprocal communication of needs and knowledge between practitioners and researchers. When combined with educational programs that focus on the weakest points in farmers' knowledge, efforts to improve on-farm soil health will be more effective.

5. Conclusion

There are many methods for assessing on-farm soil health, each with its own strengths and weaknesses. Using a combination of soil health tests would allow the strengths of some tests to compensate for the weaknesses of others, for example, assessing PLFA alongside the CSHA, or the CSHA along with an in-field scorecard. When making soil management decisions, farmers will draw on a combination of their own observations, habitual practices and soil testing when available. To improve on-farm soil management, soil health programs should endeavour to be accessible and useful channels of open communication.

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Appendix A: Additional Soil Test Results: PEI Analytical Laboratory Data & PLFA Analysis

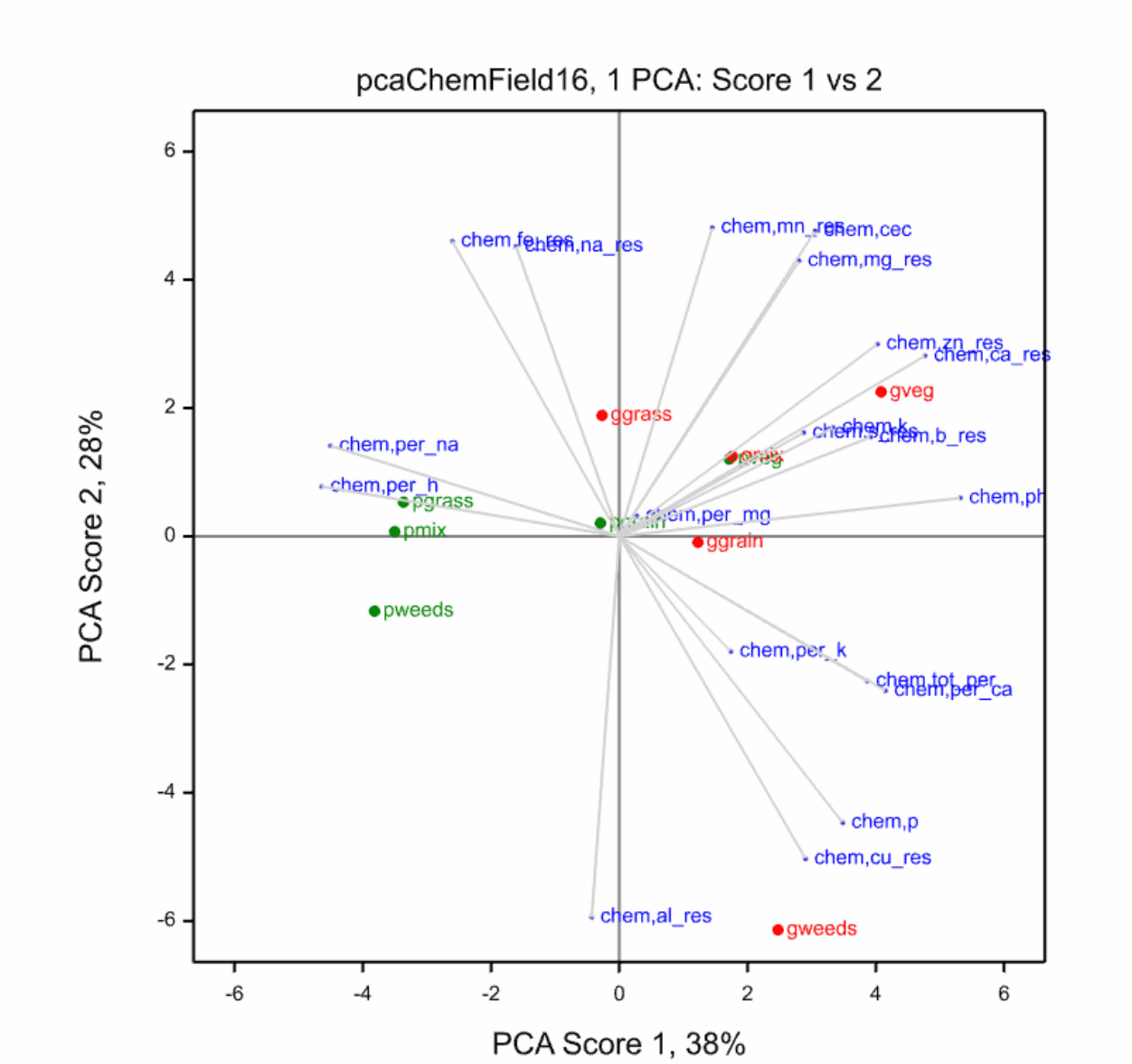
Table A1. Additional results from the PEI Analytical Laboratory.

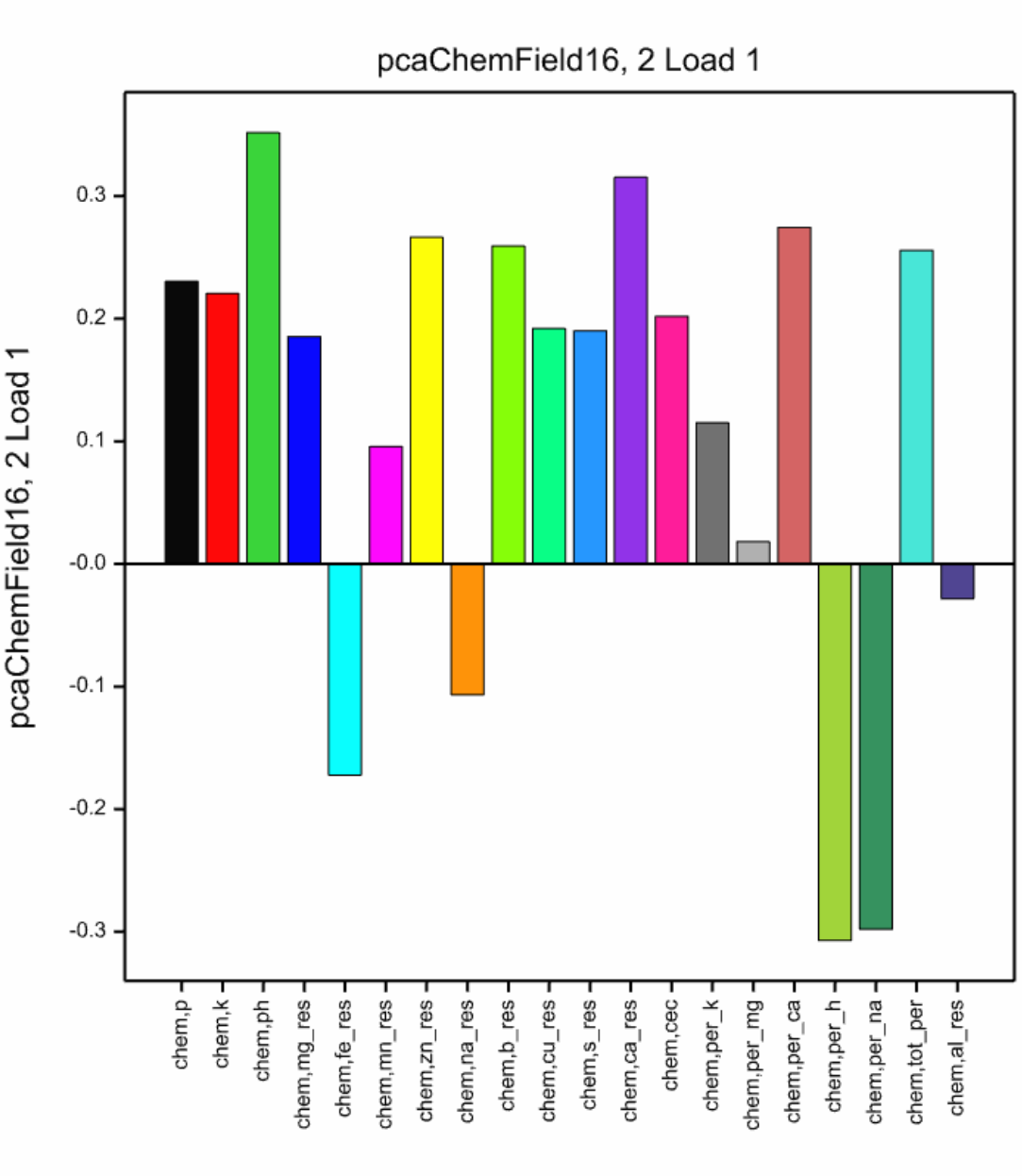
Variable	Mean	SE Mean	St. Dev.	Minimum	Maximum
Sodium (ppm)	35.28	6.36	52.48	14.00	337.00
Boron (ppm) *	0.73	0.05	0.42	0.20	2.20
Copper (ppm) *	2.39	0.30	2.43	0.40	11.40
Zinc (ppm)	3.45	0.47	3.91	0.60	19.30
Calcium (ppm) *	1455.32	82.76	682.42	213.00	4443.00
Aluminum (ppm)	1284.09	43.39	357.84	443.00	2205.00
Buffer pH *	6.98	0.03	0.25	6.10	7.50
CEC (meq/100 g) *	11.01	0.52	4.25	5.00	27.00
% Potassium	2.66	0.20	1.63	0.70	7.80
% Magnesium	13.06	0.61	5.02	4.50	31.00
% Calcium	66.36	2.03	16.72	16.80	88.50
% Hydrogen	12.41	2.25	18.59	0.00	75.70
% Sodium	1.28	0.12	0.98	0.60	6.20
% Total Base Saturation	82.09	2.09	17.27	22.40	99.30

* significant difference between good and poor soils at p=0.05

Appendix B: Data Reduction using principle component analysis of CSHA, PLFA and soil chemistry data.

PCA of Chem data




pcaChemField16, 2 Load 1
pcaChemField16, 2 Load 1
0.3
0.2
0.1
-0.0
-0.1
-0.2
-0.3
chem,p
chem,k
chem,ph
chem,mg_res
chem,fe_res
chem,mn_res
chem,zn_res
chem,na_res
chem,b_res
chem,cu_res
chem,s_res
chem,ca_res
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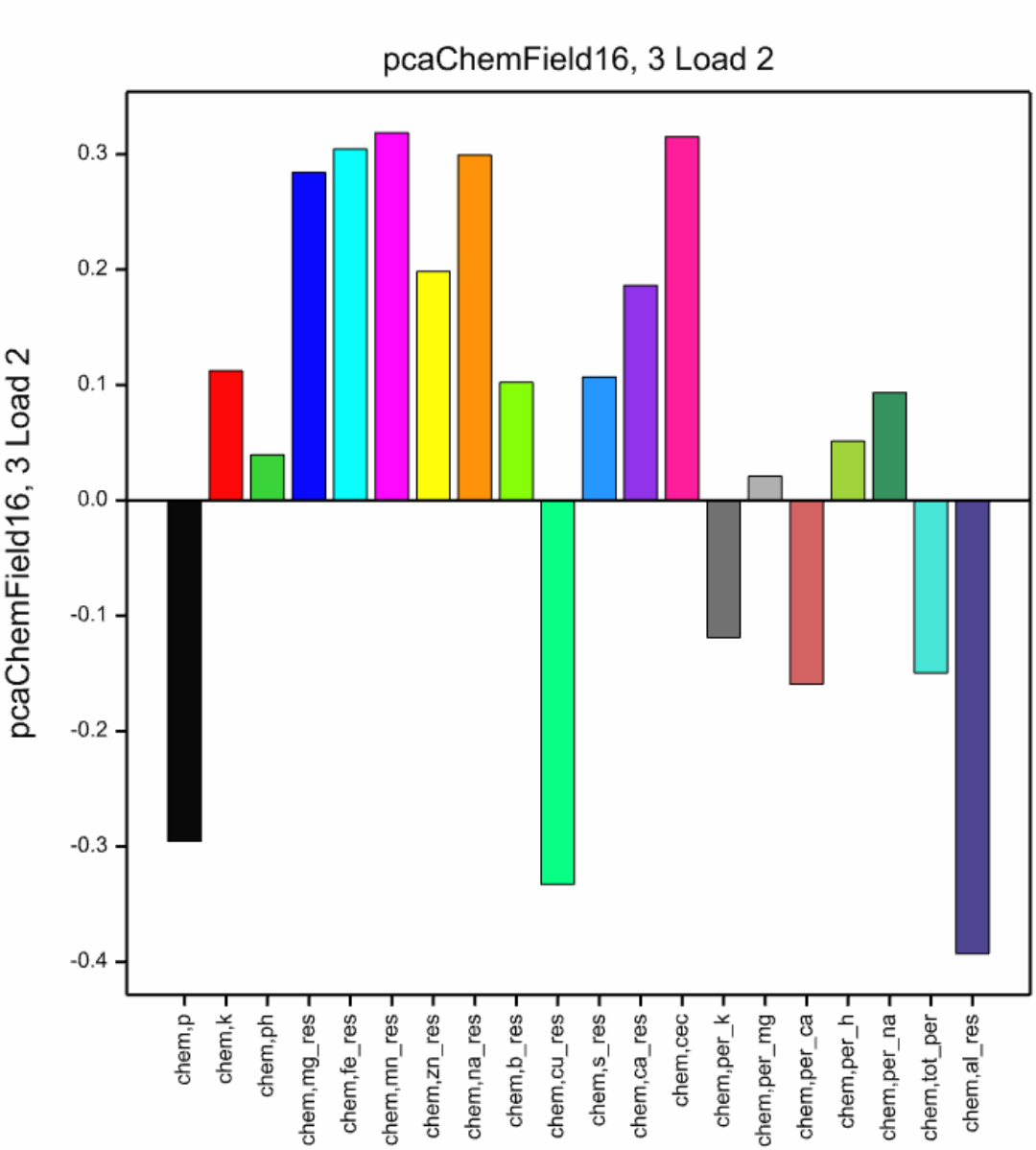
chem,per_h
chem,per_na
chem,tot_per
chem,al_res


pcaChemField16, 3 Load 2
pcaChemField16, 3 Load 2
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
chem,p
chem,k
chem,ph
chem,mg_res
chem,fe_res
chem,mn_res
chem,zn_res
chem,na_res
chem,b_res
chem,cu_res
chem,s_res
chem,ca_res
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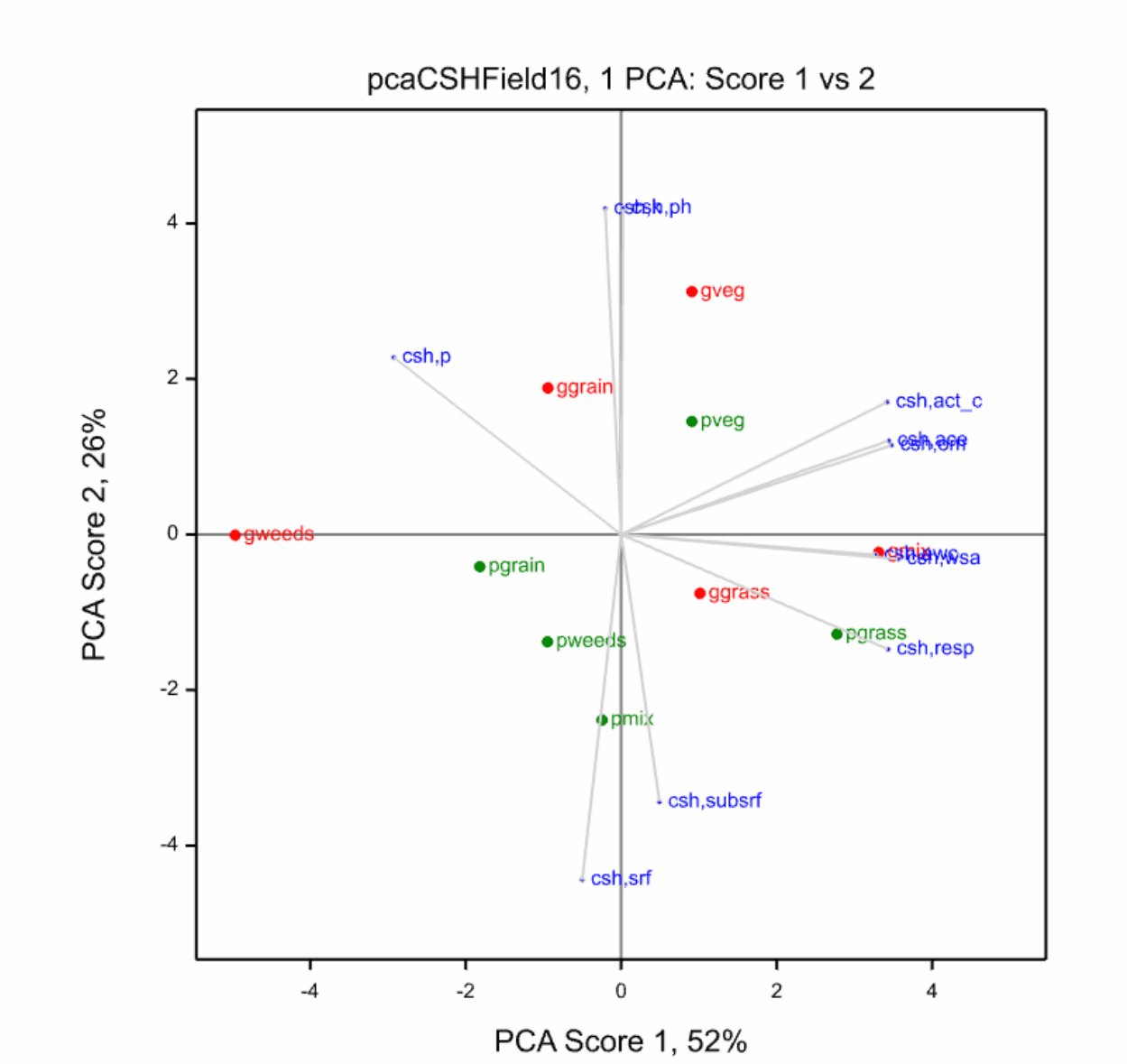
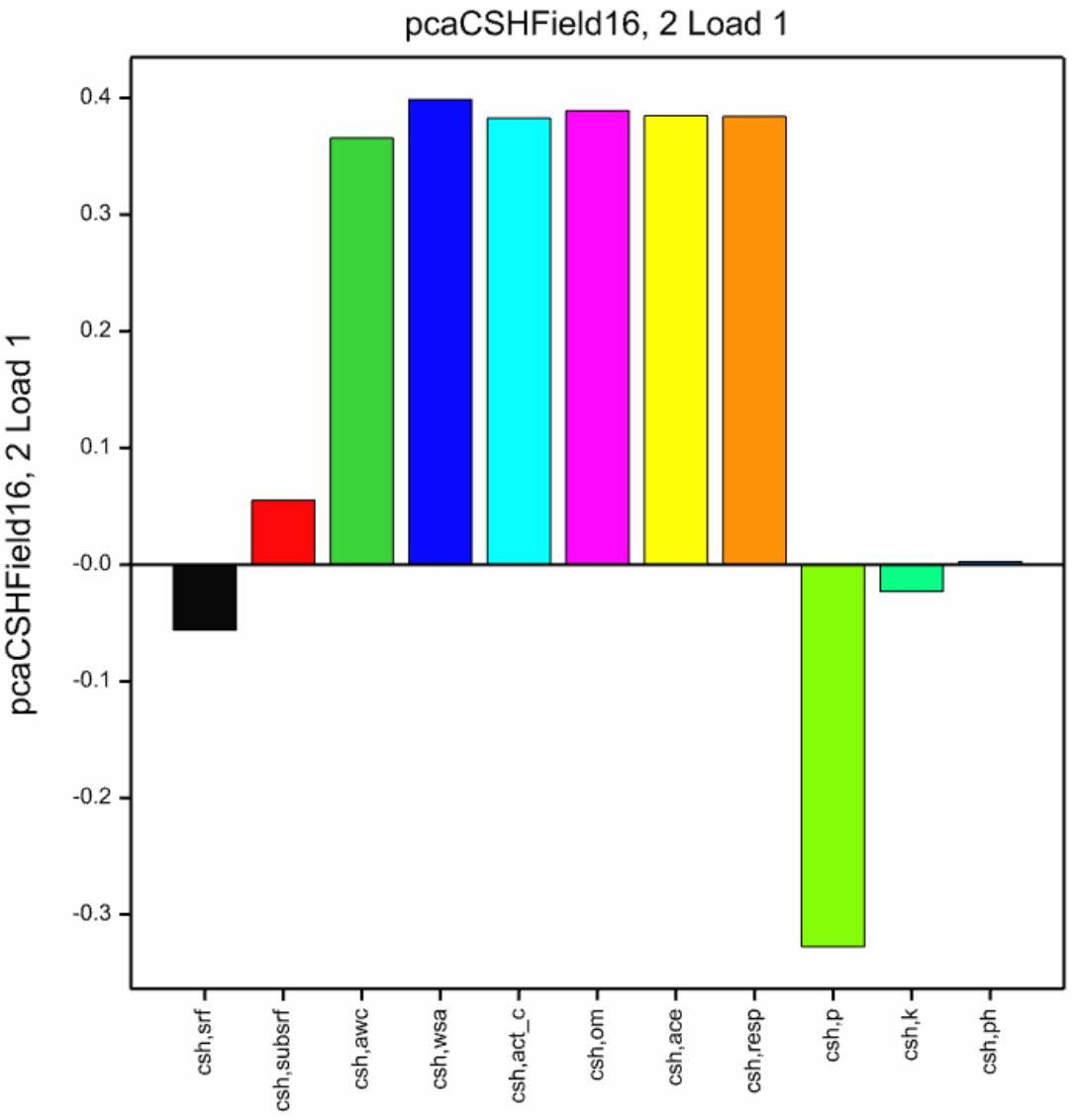
chem,per_na
chem,tot_per
chem,al_res

PCA of CSHA data

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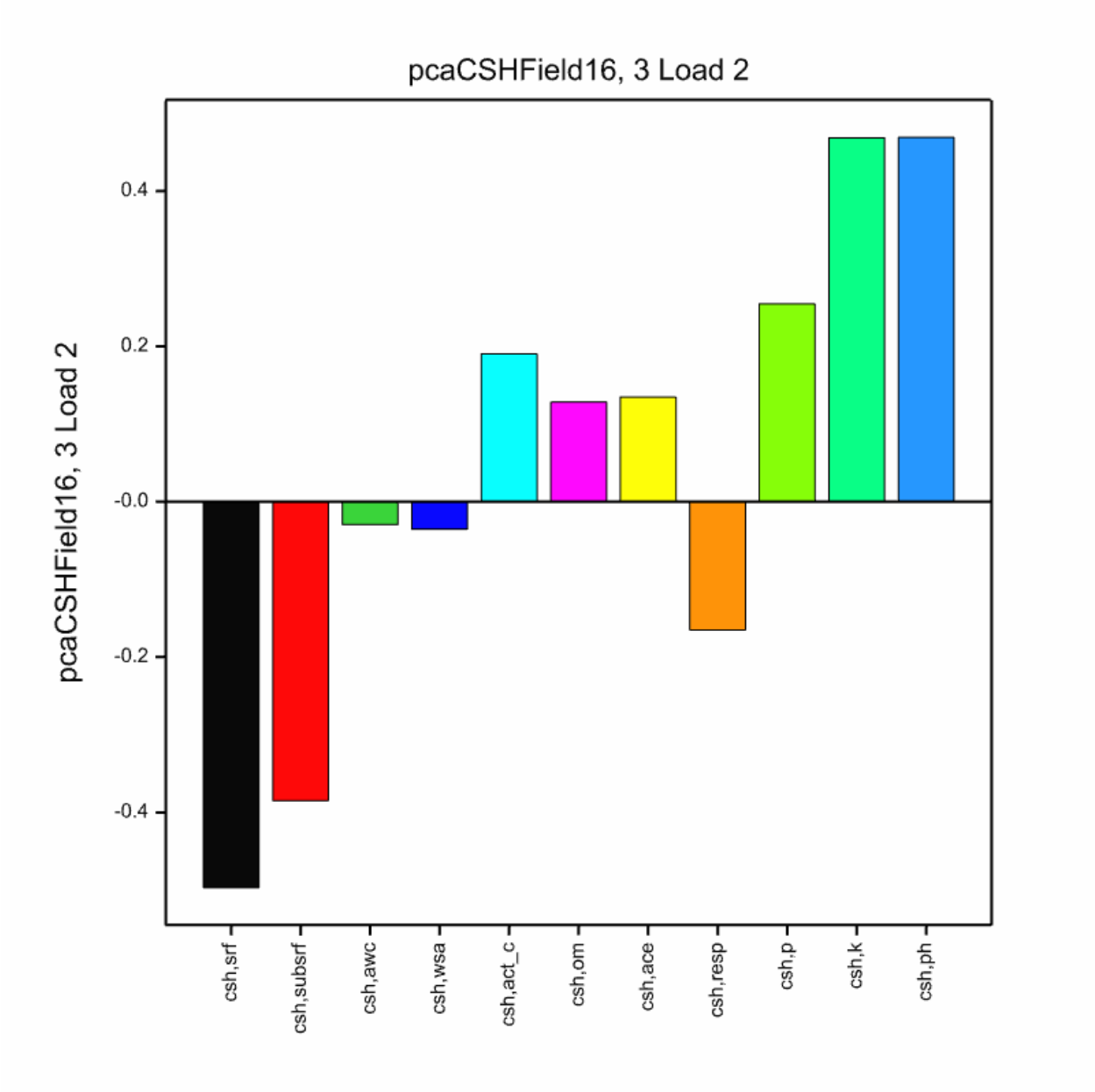
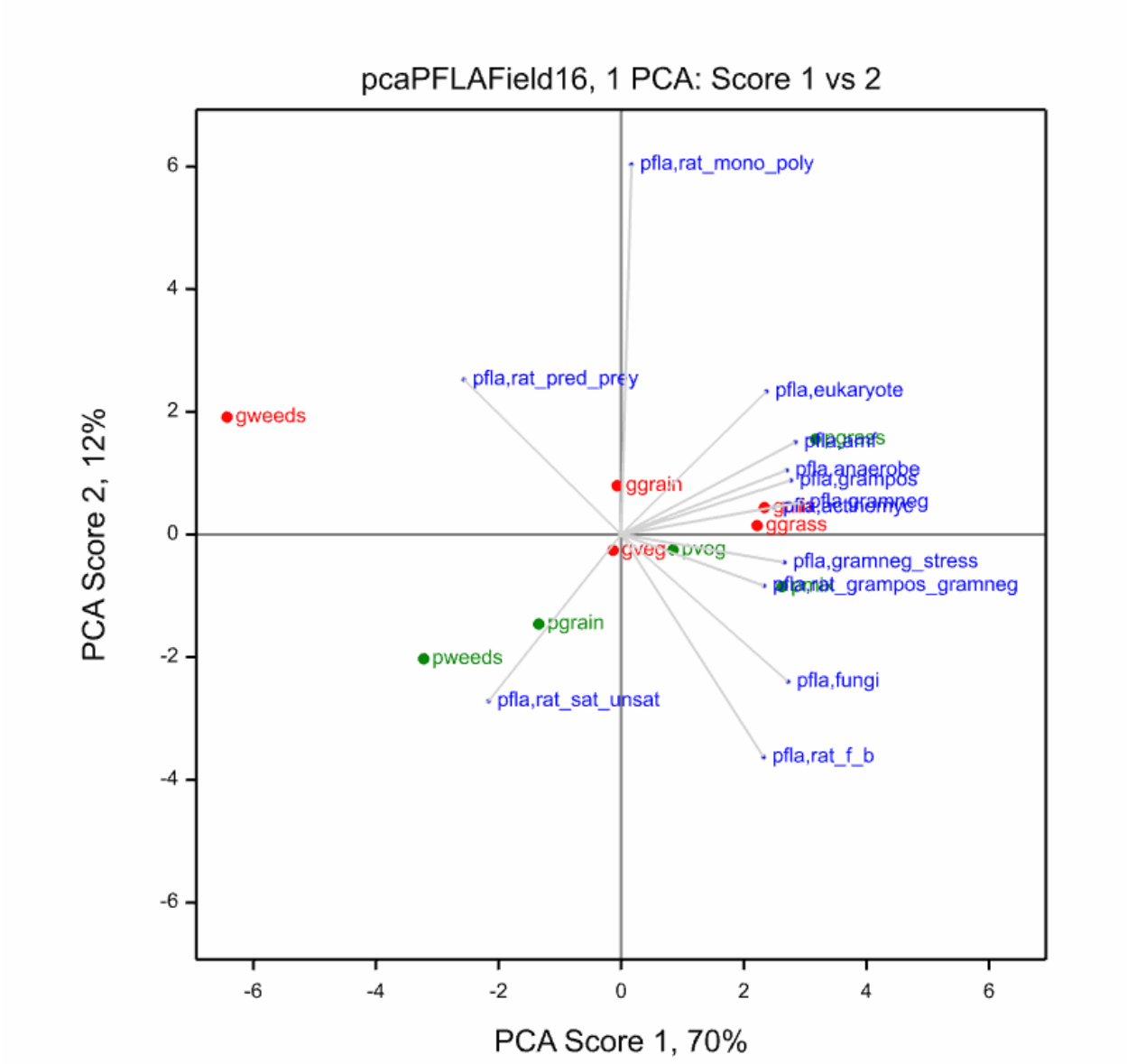
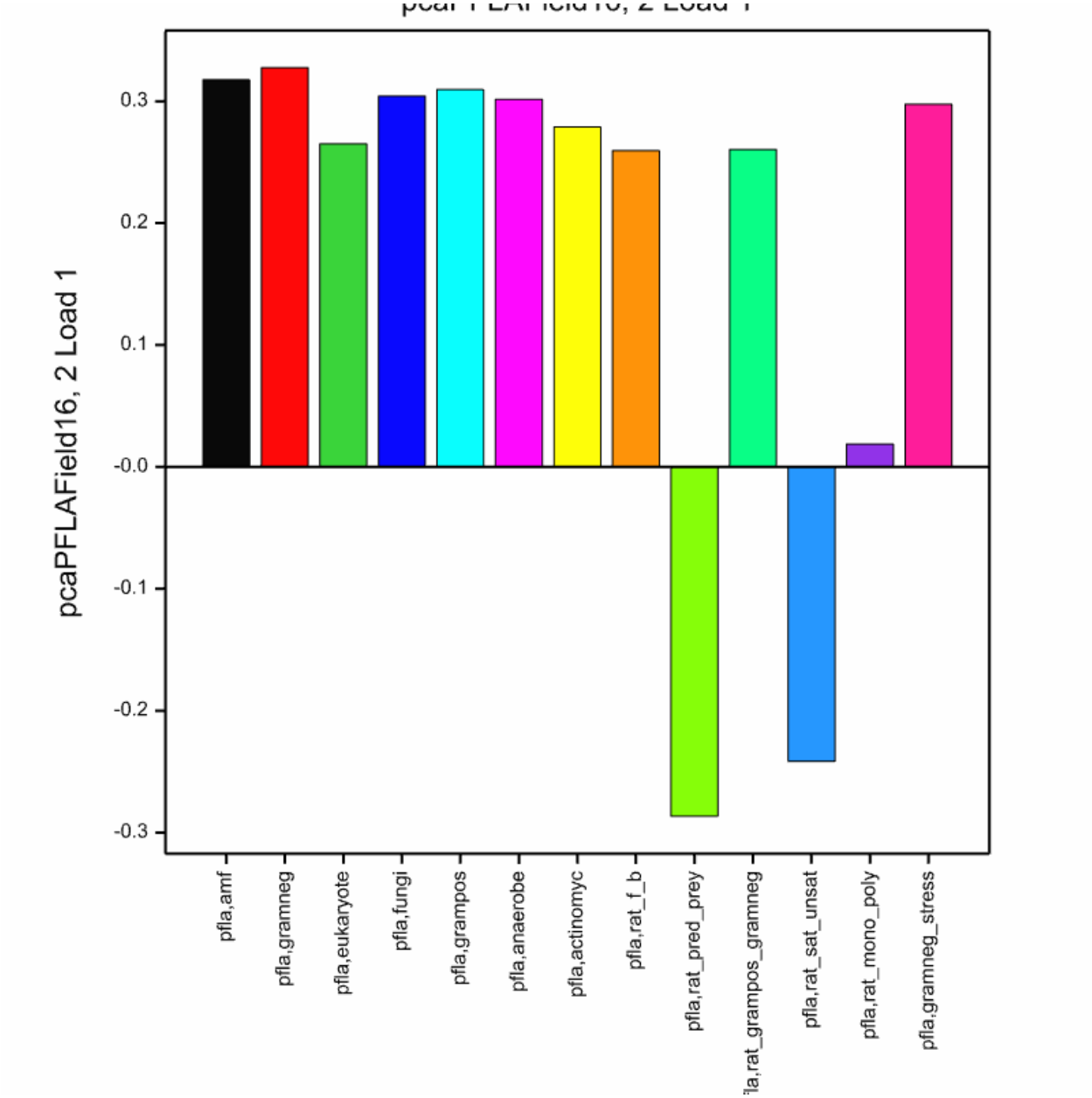
pcaCSHField16, 2 Load 1
0.4
0.3
0.2
0.1
-0.0
-0.1
-0.2
-0.3
csh,srf
csh,subsrf
csh,awc
csh,wsa
csh,act_c
csh,om
csh,ace
csh,resp
csh,p
csh,k
csh,ph


pcaCSHField16, 3 Load 2
pcaCSHField16, 3 Load 2
0.4
0.2
-0.0
-0.2
-0.4
csh,srf
csh,subsrf
csh,awc
csh,wsa
csh,act_c
csh,om
csh,ace
csh,resp
csh,p
csh,k
csh,ph

PCA of PLFA data




pcaPFLAField16, 2 Load 1
0.3
0.2
0.1
-0.0
-0.1
-0.2
-0.3
pfla,amf
pfla,gramneg
pfla,eukaryote
pfla,fungi
pfla,grampos
pfla,anaerobe
pfla,actinomyc
pfla,rat_f_b
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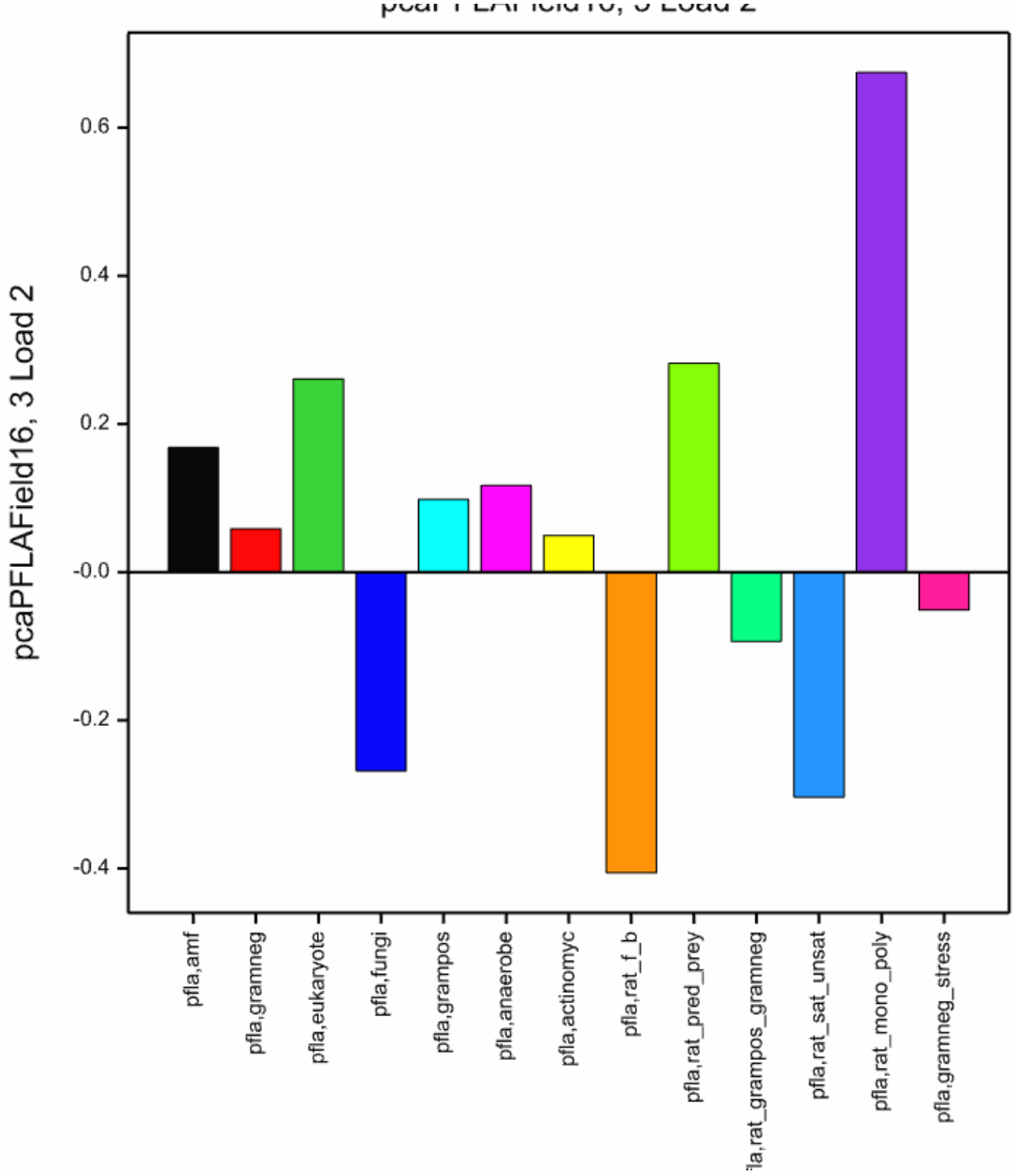
pfla,rat_sat_unsat
pfla,rat_mono_poly
pfla,gramneg_stress


pcaPFLAField16, 3 Load 2
0.6
0.4
0.2
-0.0
-0.2
-0.4
pfla,amf
pfla,gramneg
pfla,eukaryote
pfla,fungi
pfla,grampos
pfla,anaerobe
pfla,actinomyc
pfla,rat_f_b
pfla,rat_pred_prey
pfla,rat_grampos_gramneg
pfla,rat_sat_unsat
pfla,rat_mono_poly
pfla,gramneg_stress

Appendix C: Raw Field Management Data

plot	prov	g_p	sand	silt	clay	rotation	crop_16	cc_16	crop_15	cc_15	crop_14	cc_14	tillage	manure	compost	lime	syn_fert	herb	insect	fung
1	nb	g	14.2	78.7	7.2	grass	per_grass	0	per_grass	0	per_grass	0	3	3	0	0	0	0	0	0
2	nb	p	10	78.8	11.3	weeds	0	weeds	0	weeds	0	weeds	3	0	0	0	0	0	0	0
3	nb	g	53.8	39	7.2	mix	leg_grass_mix	0	leg_grass_mix	0	leg_grass_mix	0	1	0	0	0	0	0	0	0
4	nb	p	61	33.9	5.1	grass	per_grass	0	per_grass	0	per_grass	0	1	0	0	0	0	0	0	0
5	nb	g	54.6	35.1	10.3	veg	veg	weeds	veg	0	per_grass	0	2	0	2	1	0	0	0	0
6	nb	p	57.4	32.4	10.1	weeds	0	weeds	0	weeds	0	weeds	2	0	0	1	0	0	0	0
7	nb	g	31.4	58.2	10.4	grain	ann_grain	leg	ann_grain	0	ann_grain	leg	1	0	0	0	3	3	0	0
8	nb	p	30.4	59.2	10.4	grain	ann_grain	leg_grass_mix	ann_grain	leg_grass_mix	ann_grain	0	1	0	0	0	3	3	0	0
9	nb	g	49.9	41.9	8.2	grain	ann_grain	0	ann_grain	0	ann_grain	0	2	0	0	0	3	3	0	0
10	nb	p	57.9	35.9	6.2	grass	per_grass	0	per_grass	0	per_grass	0	1	2	0	0	3	0	0	0
11	nb	g	46.7	44.1	9.2	legume	leg	0	leg	0	ann_grain	0	2	0	0	0	2	1	0	0
12	nb	p	47.7	44	8.4	mix	leg_grass_mix	0	leg_grass_mix	0	per_grass	0	1	2	0	0	1	1	0	0
13	nb	g	47.2	46.7	6.1	veg	veg	weeds	per_grass	nonleg_grm	veg	weeds	2	1	0	2	0	0	0	0
14	nb	p	42.9	45.8	11.2	grass	per_grass	0	per_grass	0	per_grass	0	1	0	0	0	0	0	0	0
15	nb	g	49	45.9	5.1	mix	leg_grass_mix	0	leg_grass_mix	0	leg_grass_mix	leg_grass_mix	1	2	0	0	2	0	0	0
16	nb	p	79.6	16.3	4.1	grass	per_grass	0	per_grass	0	per_grass	0	1	3	0	0	0	0	0	0
17	nb	g	58.1	37.8	4.1	grass	leg_grass_mix	0	leg_grass_mix	0	leg_grass_mix	0	1	3	0	0	0	0	0	0
18	nb	p	49.6	42.2	8.2	grass	per_grass	0	per_grass	0	per_grass	0	1	3	0	0	0	0	0	0
19	ns	g	57	38.9	4.1	veg	veg	nonleg_grm	per_grass	0	per_grass	0	2	0	1	1	1	0	0	0
20	ns	p	56	41	3.1	veg	veg	nonleg_grm	per_grass	0	per_grass	0	3	0	1	1	1	0	0	0
21	ns	g	25.8	62	12.2	grass	per_grass	0	per_grass	0	per_grass	0	2	0	0	0	3	0	0	0
22	ns	p	20.3	61.9	17.8	grass	per_grass	0	per_grass	0	per_grass	0	1	3	0	0	0	0	0	0
23	ns	g	68.4	29.6	2	veg	veg	nonleg_grm	veg	0	veg	0	3	0	3	0	3	0	0	0
24	ns	p	69.6	29.4	1	weeds	0	nonleg_grm	veg	0	veg	0	3	0	1	1	3	0	1	0
25	ns	g	18.2	65.4	16.4	grass	per_grass	0	per_grass	0	per_grass	0	1	3	0	0	0	0	0	0
26	ns	p	79.8	17.2	3	grass	per_grass	0	per_grass	0	per_grass	0	1	0	0	0	0	0	0	0
27	ns	g	81.8	13.1	5.1	weeds	0	nonleg_grm	veg	0	veg	0	3	0	0	0	0	1	0	0
28	ns	p	70.6	25.4	4.1	veg	veg	0	0	0	0	nonleg_grm	3	0	0	0	0	3	1	2
29	ns	g	83.8	11.1	5.1	grain	ann_grain	0	veg	0	veg	0	3	1	0	1	3	2	1	0
30	ns	p	72.8	20.2	7.1	grain	ann_grain	0	ann_grain	0	ann_grain	0	2	0	0	0	3	2	0	0
31	ns	g	62.7	27.2	10.1	veg	veg	0	veg	nonleg_grm	veg	nonleg_grm	3	1	0	0	2	2	0	0
32	ns	p	78.9	17.1	4	veg	veg	0	veg	0	veg	nonleg_grm	3	1	0	0	2	2	0	0
33	ns	g	48.3	47.7	4.1	grass	per_grass	0	per_grass	0	per_grass	0	1	0	0	0	0	0	0	0
34	ns	p	45.2	47.7	7.1	grass	per_grass	0	per_grass	0	per_grass	0	1	0	0	0	0	0	0	0

plot	prov	g_p	sand	silt	clay	rotation	crop_16	cc_16	crop_15	cc_15	crop_14	cc_14	tillage	manure	compost	lime	syn_fert	herb	insect	fung
35	ns	g	49.1	46.8	4.1	veg	veg	per_grass	veg	per_grass	veg	0	2	0	0	0	0	0	0	0
36	ns	p	47.4	45.5	7.1	grass	fallow	0			per_grass		1	0	0	0	0	0	0	0
37	ns	g	45.9	49	5.1	grass	veg	0	veg	0	fallow	0	1	0	0	0	0	0	0	0
38	ns	p	44.2	51.7	4.1	veg	fallow	0	fallow	0	fallow	0	3	0	2	0	0	0	0	0
39	ns	g	46.5	48.4	5.1	mix	0	leg_grass_mix	veg	nonleg_grm	veg	nonleg_grm	2	0	0	0	0	0	0	0
40	ns	p	44.3	48.4	7.2	veg	veg	leg_grass_mix	veg	0	veg	nonleg_grm	2	0	0	0	0	0	0	0
41	ns	g	59.1	35.8	5.1	grass	per_grass	0	per_grass	0	per_grass	0	1	0	0	0	2	0	0	0
42	ns	p	58.1	37.8	4.1	grass	per_grass	0	per_grass	0	per_grass	0	1	0	0	0	2	0	0	0
43	pe	g	60.8	33.1	6.1	grass	ann_grain	0	per_grass	0	per_grass	0	3	0	0	0	0	0	0	0
44	pe	p	59.7	33.6	6.6	grain	ann_grain	0	ann_grain	0	per_grass	0	3	0	0	0	0	0	0	0
45	pe	g	56.7	37.2	6.1	veg	veg	0	per_grass	0	ann_grain	leg	3	0	0	0	1	0	0	0
46	pe	p	50.6	41.3	8.2	veg	veg	0	per_grass	0	ann_grain	leg	3	0	0	0	1	0	0	0
47	pe	g	59.7	34.7	5.6	grain	ann_grain	leg	per_grass	0	per_grass	0	3	0	0	0	0	0	0	0
48	pe	p	59.4	35.6	5.1	grain	ann_grain	0	ann_grain	0	ann_grain	0	3	0	0	0	0	0	0	0
49	pe	g	44.3	50.6	5.1	grass	per_grass	0	per_grass	0	per_grass	0	1	2	0	0	3	0	0	0
50	pe	p	46.3	44.5	9.2	grass	per_grass	0	per_grass	0	per_grass	0	1	1	0	0	3	0	0	0
51	pe	g	48.9	43.1	8	veg	veg	nonleg_grm	veg	leg_grass_mix	veg	leg_grass_mix	2	0	3	0	0	0	0	0
52	pe	p	46.9	42.8	10.3	veg	veg	nonleg_grm	veg	nonleg_grm	veg	0	2	0	3	0	0	0	0	0
53	pe	g	55.9	33.9	10.3	mix	0	leg_grass_mix	ann_grain	0	ann_grain	0	1	1	0	0	1	1	0	1
54	pe	p	57.2	31.6	11.2	mix	0	leg_grass_mix	ann_grain	0	leg_grass_mix	0	1	0	0	0	1	1	0	1
55	pe	g	65	30.4	4.6	grain	ann_grain	0	ann_grain	0	leg	leg	3	1	0	0	0	2	0	0
56	pe	p	67.6	24.8	7.6	grain	ann_grain	0	ann_grain	0	leg	leg	3	1	0	0	0	2	0	0
57	pe	g	49.8	38.8	11.4	veg	veg	0	0	nonleg_grm	veg	0	3	0	2	0	1	0	1	0
58	pe	p	56.6	34	9.4	veg	veg	0	veg	nonleg_grm	veg	leg_grass_mix	3	0	2	0	1	0	1	0
59	pe	g	63.3	30	6.7	veg	veg	nonleg_grm	veg	nonleg_grm	veg	nonleg_grm	3	3	0	0	0	0	0	0
60	pe	p	59.8	34	6.2	potato	ann_grain	nonleg_grm	0	nonleg_grm	per_grass	0	3	0	0	0	0	0	0	0
61	pe	g	68.9	23.4	7.6	grass	per_grass	0	per_grass	0	ann_grain	0	1	0	0	0	0	0	0	0
62	pe	p	63.2	28.1	8.7	grain	ann_grain	0	veg	0	ann_grain	0	1	0	0	0	0	0	0	0
63	pe	g	48.6	43.8	7.6	veg	veg	0	veg	0	veg	0	3	0	0	0	3	0	0	0
64	pe	p	48.7	41.7	9.7	weeds	0	nonleg_grm	veg	0	fallow	0	3	0	0	0	3	0	0	0
65	pe	g	54.7	39.6	5.7	veg	veg	leg	veg	nonleg_grm	veg	nonleg_grm	3	3	3	0	0	0	0	0
66	pe	p	55.6	37.7	6.7	weeds	fallow	0	0	nonleg_grm	veg	0	3	0	0	0	0	0	0	0
67	pe	g	61.2	27.6	11.2	grass	leg_grass_mix	0	ann_grain	per_grass	ann_grain	0	3	0	1	1	2	1	1	1
68	pe	p	61.2	29.6	9.2	weeds	0	nonleg_grm	ann_grain	0	leg_grass_mix	0	1	1	0	1	2	1	1	1

Appendix D: Soil Health Scorecard

1. What level of yields do you generally see from this field?
    - 4 High yields: above industry average.
    - 2 Moderate yields: around industry average.
    - 0 Low yields: below industry average.

2. How would you rate the texture of this soil?
    - 0 Texture is a problem, extremely sandy, clayey or rocky
    - 2 Texture is too heavy or too light, but presents no problem
    - 4 Texture is loamy

3. When this soil is moist, what colour is it?
    - 0 Yellow, pale brown or light grey
    - 2 Red, grey or brown
    - 4 Dark brown, very dark grey, or black

4. How easy is it to till or work this soil?
    - 0 Plow scours hard, soil never works down
    - 2 Soil grabs plow, difficult to work, needs extra passes
    - 4 Plow field in higher gear, soil flows & falls apart

5. About what degree of compaction best describes this soil?
    - 0 Soil is very compact, difficult to get into, stubborn hardpan present
    - 2 Soil packed down, thin hardpan or plow layer
    - 4 Soil is loose, no hardpan present

6. What is the drainage like in this soil?
    - 0 Poor drainage, soil is often waterlogged or oversaturated
    - 2 Soil drains slowly, slow to dry out
    - 4 Soil drains at good rate for crops, water moves through

7. What would you estimate the water-holding capacity of this soil to be?
    - 0 Soil dries out very fast, droughty
    - 2 Soil dries out moderately fast, drought prone in dry weather
    - 4 Soil holds moisture well, a good buffer in dry weather

8. What type of structure best describes this soil?
    - 0 Soil is cloddy with big chunks, or dusty and powdery
    - 2 Soil is lumpy or does not hold together
    - 4 Soil is crumbly, granular

9. What would you estimate the levels of N, P and K to be in this soil?
    0 Two or more nutrient levels very low, limiting crop growth
    2 Soil test values are below recommended levels, need extra inputs
    4 All nutrient levels at recommended levels
10. What would you estimate the levels of micronutrients to be in this soil?
    0 Severe shortages of trace minerals (zinc, boron, etc.)
    2 Micronutrients at a minimal level or not balanced
    4 Levels of micronutrients high and balanced

11. What would you estimate the pH of this soil to be?
    0 Strongly acid (pH less than 5.5)
    2 Moderately acid (pH 5.6 – 6.5)
    4 Neutral (pH 6.6 – 7.5)

12. About what percentage of organic matter is in this soil?
    0 Organic matter less than 1%
    2 Organic matter between 1.1 – 4%
    4 Organic matter greater than 4%

13. About how much earthworm activity would you estimate in this soil?
    0 No activity. No worm holes or castings present.
    2 Some activity. Few worm holes or castings present.
    4 Much activity. Many worm holes or castings present.

14. What does this soil smell like?
    0 Soil has a sour, putrid or chemical smell
    2 Soil has no odor or a mineral smell
    4 Soils has an earthy, sweet, fresh smell

15. How healthy are the roots of the plants in this soil?
    0 Plant roots appear unhealthy (brown, diseased, spotted), poorly developed, balled up
    2 Plant roots are shallow, at hard angles, development limited, few fine roots
    4 Plant roots are deep, fully developed with lots of fine root hairs

16. What is the level of biological activity (fungi, bacteria, insects, earthworms) in this soil?
    0 Soil shows little biological activity, no signs of soil life
    2 Moderate biological activity
    4 High biological activity

17. What is the appearance of the crops in this soil (during average rainfall levels)?

0 Overall crop is poor, stunted, discoloured, in an uneven stand

2 Overall crop is light green, small, in a thin stand

4 Overall crop is dark green, large, tall, in a dense stand

Appendix E: Interview guide from first farmer interviews.

Thank you for taking the time to do this interview with me. There's about 7 questions, all related to your thoughts and ideas about soil. Most of the questions are very open ended so if you ever feel like you want to say more or keep talking feel free to interrupt me or keep going. I'm here to listen to you, so there are absolutely no wrong answers. The interview itself is pretty structured, but afterwards we can have a more casual conversation if you have any questions or comments. So the first question I want to ask you is …

Question 1: How do you know what is a good soil and what is a poor soil?

Question 2: So if we were to walk out to a piece of land right now and look at the soil, what specific things do you look for or think about when trying to assess it?

Question 3: Have you ever made a management decision because you wanted to improve your soil and if so, what was the decision?

Question 4: Do you ever conduct soil testing on your farm? If so, where and how often?

If Yes, Question 5: How do you use the soil test information?

Question 6: Sometimes people like to differentiate between the terms "soil fertility", "soil quality" and "soil health". Have you ever heard or read about the term "soil health"?

If Yes, Question 7: How would you define soil health?

If No: How would you define soil quality?

Appendix F: Seventy-three soil indicators mentioned by farmers in the online survey

Category	Indicators
Biological	Earthworms
	SOM
	Biological activity
	Soil life
	Microbial presence/abundance
	Fungal activity
	Root health
	Bacterial activity
	Decomposition rate
	Disease
	Algae growth
	Beneficial insects
	Fungi:bacteria ratio
	Insect activity
	Insect pressure
	Microbial diversity
	Protozoa
	Respiration
	Root penetration
	Soil biodiversity
	Spiders
Chemical	pH
	Soil test
	Macronutrients
	Micronutrients
	CEC
	Fertility
	Mineralization
	Minerals
	Nutrient cycling
	Salt presence
	Soil chemistry
	Soil toxins
	Leaching
Physical	Drainage
	Structure/Aggregation/Crumble
	Water holding

	Texture
	Friability/Tilth
	Erosion
	Hardpan
	Water absorption/penetration
	Clay presence
	Loamy
	Rockiness
	Soil moisture
	Soil pores
	Topsoil depth
	Water stable aggregates
Aboveground	Plant/crop
	growth/health
	Compaction
	Yield
	Aeration/Air-holding
	Weeds
	Fruit production speed
	Pest control
	Plant diversity
	Plant tissue analysis
	Seed germination
	Seedling growth
Sensory	Soil
	appearance
	Smell
	Colour
	Touch/Feel
	Balance
	Soil richness
Management-based	Ease of tillage/workability
	Crop rotation history
	Manmade substances
	Additives needed
	Compost application
	Tile drainage
	Tillage needed