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Safeguarding Potato Cropping Systems in the Pacific Northwest Through Improved Soil Health

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Executive Summary

The Pacific Northwest (PNW) is a major producer of potatoes for processing and the fresh market. Consumer preferences for sustainably produced foods, a reported slowing of rates of yield growth, and the goal of continuing to expand production in the region have led to an increased interest by industry members in opportunities for enhancing soil health in potato cropping systems. This report summarizes relevant literature on soil health, with a specific focus on PNW potato systems, and provides initial recommendations for directing future research funding.

There is not scientific consensus on which indicators should be used to measure soil health, but soil health assessments commonly include measurement of physical, chemical and biological indicators. Additionally, soil health assessments developed in other regions may not be applicable to the production methods and challenges of PNW cropping systems. Improved translation of soil health indicators into specific management recommendations that lead to improved crop quality and yield are also lacking.

Improving soil health in potato production poses a particular challenge since potato production involves intensive cultivation, leaves minimal residue on the fields after harvest, and, to meet market-based demands, must involve management of soilborne potato pathogens that affect cosmetic quality. Short crop rotations, driven by the economics of production, tend to exacerbate soilborne disease problems and have led to a reliance on soil fumigation to manage soilborne pathogens.

The literature on soil health in potato cropping systems in the PNW is largely related to the management of soilborne pathogens by crop rotation and cover cropping. Though soil health discussed in the context of potato cropping systems sometimes refers to soils with low soilborne disease pressure, it is important to note that disease pressure is only one aspect of soil health, which is defined as "the continued capacity of 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" (Doran et al. 1996). In some discussions of soil health, the assumption is made that soils having attributes associated with soil health will not have problems with soilborne pathogens, this oversimplifies the relationship between soil health and soilborne pathogens. Thus, it may be helpful to think of practices for improving soil health as just some of the many management strategies in a grower's

toolkit for improving crop yield and quality. The broader set of approaches generally thought to improve soil health in cropping systems also includes strategies such as minimizing soil disturbance, keeping soil covered, maximizing the duration of living roots, and maximizing the diversity of crops within rotation.

Crop rotations vary widely across the PNW and are an important factor for improving soil health and controlling soilborne pathogens, but the economics of potato production often drive growers to use relatively short rotations and rely heavily on soil fumigants. Choice of rotation crops, for example to maximize residue inputs or assist in controlling soilborne pathogens, may be an important avenue for improving soil health. Site specific soil fumigation may hold some promise for control of some pathogens though its cost effectiveness will likely depend on how intensive the soil sampling needs to be to determine pathogen levels, appropriate timing, and the development of effective site-specific application technologies. Opportunities also may exist for improving management of crop residues and reducing tillage during the years when potato is not grown. Extending rotations may be the least feasible approach to improving soil health from an economic perspective, but where extended rotations and careful selection of rotation crops that assist in managing soilborne pathogens lead to an increase in subsequent potato yields, economic returns over the course of the whole rotation may be increased.

Use of cover crops, particularly the incorporation of cover crops as green manures, has been extensively researched in potato systems because they add organic matter, control wind erosion, improve water infiltration, scavenge residual nitrogen, and, in certain cases, suppress soilborne pathogens. Incorporating green manure cover crops prior to planting potato seems to have gained a small foothold in some areas of the PNW, particularly in the Columbia Basin and eastern Idaho, with mustard and oilseed radish being the species most frequently used for the general purpose of improving potato yield by controlling soilborne pathogens, particularly *Verticillium dahliae*. Efficacy of this approach seems to be dependent on soil type and soil conditions and most growers experience a learning curve associated with managing green manures effectively. Most of the recent research on cover crops in the PNW has occurred in the Columbia Basin, and more work could be done in other areas to identify best practices for including cover crops in specific potato cropping systems (e.g., cover crop species, planting date, nitrogen availability following incorporation, efficacy of green manure against various soilborne pathogens in different soil types). Measuring cover crop effects on potato yield, quality, soilborne disease occurrence, soil quality indicators, and net returns for growers also would be beneficial.

Opportunities to incorporate organic amendments such as compost and manure in potato rotations exist, especially in areas in close proximity to livestock agriculture. The literature supports the idea that application of manure and compost can improve soil health, but the belief that manure application will increase plant disease incidence and the added complexity of matching crop nitrogen need to nitrogen availability from an organic source limits their use. In some areas with close proximity to livestock agriculture (e.g., the Magic Valley and Treasure Valley of Idaho), use of manure in potato rotations is becoming common, but potential exists to optimize its application for potato yield and quality.

Practices that have been used for improving soil health include: reducing tillage; adjusting crop rotation length, species composition, and residue return; and using cover crops, green manures, and organic amendments. Further research is needed to learn how these practices affect soil health, soilborne pathogens, yield and quality of potatoes, and net returns within diverse PNW potato production areas. Future research funding on this topic should be directed toward projects with the following goals:

1) Elucidate the relationship between practices that improve soil health and soil health indicators, soilborne pathogens, and potato yield and quality in PNW potato systems.

2) Develop a soil health assessment approach or calibrate an existing assessment method for use in PNW potato systems and establish a baseline understanding of soil health in PNW potato systems.

3) Gather additional information to characterize distinct potato cropping systems in the PNW and identify specific soil health challenges and opportunities unique to each system.

4) Develop a better understanding of the barriers that currently prevent adoption of practices known to improve soil health and address these barriers. Quantify the tradeoffs that exist for particular practices, or suites of practices, in order to provide PNW potato growers with important decision-making tools for optimizing tradeoffs.

5) Establish long-term research and demonstration sites in the various potato cropping systems in the PNW to provide information on both economic and agronomic changes resulting from these approaches.

In the pursuit of Goals 1, 4, and 5, above, two tiers of possible changes that can be made to improve potato production through soil health may be helpful to consider: incremental changes and whole-system changes. Incremental change involves modifications to one part of the cropping system that are relatively low risk to growers (e.g., inclusion of cover crops, inclusion of organic amendments, and variable rate soil fumigation). However, because there are limitations on improving the biological components of soil health while fumigation is being used, whole system changes should be considered as well. Whole-system changes involve incorporating multiple approaches with the goal of manipulating the soil chemical, physical, and biological environment enough to eliminate the need for fumigation. Due to the long-term nature of soil health impacts, goal 5, the establishment of long-term research and demonstration sites, is an important step toward substantive research in soil health.

This report outlines the state of the science on soil health in potato production systems in the PNW and provides initial recommendations for directing future research funding. The authors recommend that the largest portion of short-term investment be directed toward Goal 1 and the related Goal 2, with longer-term investment directed toward Goals 3, 4, and 5. Because it is not possible to understand all of the precise reasons for knowledge gaps from a review of the scientific literature, the authors of this report suggest that further discussion occur between industry representatives and researchers working in PNW potato production systems, using this report as a guide, to determine specific research gaps within Goals 1 and 2 that offer the best potential return on investment.

Introduction

The Pacific Northwest (PNW) is an important area of U.S. potato (*Solanum tuberosum*) production. In 2016, about 134 million tons of potatoes (66% of the total U.S. production) were harvested in the PNW on 532,000 acres (58% of the total acreage of harvested potatoes in the U.S.) (USDA NASS 2017). Potato industry representatives report that rates of yield growth have slowed in recent years. Analysis of USDA NASS data shows that average potato yield growth appears to have plateaued in Oregon and Washington over the past 10 years, while remaining relatively steady in Idaho (Figure 1, Table 1). This slowing of yield growth in some areas, combined with limitations on additional new acreage that can be brought into production, place constraints on the continued expansion of the potato industry in the region. Furthermore, consumer preferences reflect increasing public concern about environmental quality and the sustainability of potato production systems. Such preferences are reflected by the companies purchasing processed potato products; they have an interest in ensuring that sustainable practices are followed and documented via measures such as sustainability audits for potato growers (O'Connell 2017). One outgrowth of these broadening consumer preferences is the Potato Sustainability Initiative, a collaboration of growers, grower organizations, processors, buyers, the National Potato Council, the Canadian Horticultural Council, and the IPM Institute of North America which works to improve the sustainability of potato production. More than 500 growers in the U.S. and Canada currently participate in this initiative, along with six processors, including JR Simplot, McCain Foods, and Lamb Weston, and two major buyers, McDonalds and Sysco (Potato Sustainability Initiative, n.d.).

Responding to the intensifying interest in improving soil health for potato cropping systems across the nation, a workshop on this topic took place in March 2017 in Ardmore, Oklahoma, jointly hosted by the Samuel Noble Research Foundation, the National Potato Council, and the Soil Health Institute. The report from this workshop is included in Appendix A of this report. The group identified the lack of a baseline understanding of soil health and the lack of standardized soil health measurements as limiting factors to adoption of alternative crop management practices. In Washington State, a workshop brought together diverse stakeholders to discuss soil health across multiple production systems in February 2018. The workshop

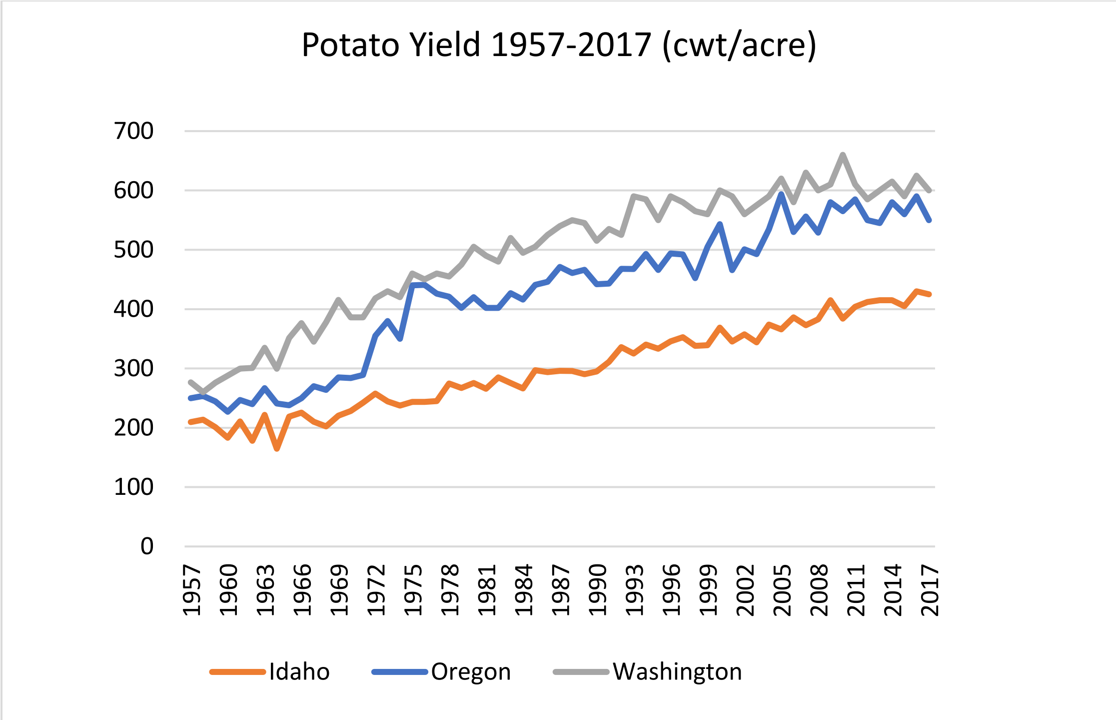

Figure 1. Potato yield 1957-2017 in Idaho, Oregon, and Washington. (Compiled from USDA NASS data)

Table 1. Average annual change in potato yield in hundredweight (cwt)/acre in Idaho, Oregon, and Washington over two time periods 1957-2007 and 2007-2017. (Compiled from USDA NASS data)

	Average annual change in yield (cwt/acre)	
	1957-2007	2007-2017
Idaho	+3	+5
Oregon	+6	-1
Washington	+7	-3

gathered input to create a coordinated plan to address soil health issues within Washington State and a regional meeting on soil health is planned for March 2019 to expand upon this effort. A summary report from the 2018 Washington Soil Health Summit is presented in Appendix B. As documented in this report, the top soil health issues identified by attendees were: a lack of diagnostic tools or tests and translating science and knowledge into implementation. The reports from both events list the following management strategies that were of interest to meeting participants for maintaining and protecting soil and water resources: the use of cover crops, alternative formulated fertilizers, organic amendments, reduced tillage, and alternative pest control strategies that reduce soil fumigation and support the competitive activities of the soil microbial community.

Thus, to provide a framework to help guide future research funding in the PNW, this review summarizes the state of the science regarding soil health in PNW potato cropping systems. A number of important soilborne fungal diseases, and nematode and insect pests of potato (Table 2) are discussed in this review in terms of their relation to soil health. However, this document is not meant to offer an exhaustive coverage of soilborne potato pathogens, diseases, or disorders affected by soil conditions. Correspondingly, this review focuses on research conducted in the PNW, though it touches on some highly relevant studies from elsewhere, as much of the research on soil health in potato systems has occurred in regions outside the PNW that have different soils, precipitation regimes, and pest pressures (e.g., Maine, Atlantic Canada).

Table 2. Disease name (of fungal pathogens), common names, and scientific names of soilborne fungal diseases, and nematode and insect pests mentioned in this report.

Organism type	Disease name	Causal organism scientific name
Bacteria	common scab	*Streptomyces scabies*
Fungi	black dot	*Colletotrichum coccodes*
	Fusarium seed piece decay	*Fusarium solani* and *F. sambucinum*
	powdery scab	*Spongospora subterranean*
	Rhizoctonia stem canker & tuber black scurf	*Rhizoctonia solani*
	silver scurf	*Helminthosporium solani*
	Verticillium wilt (part of potato early dying complex)	*Verticillium dahliae*
	white mold	*Sclerotinia sclerotiorum*
Oomycetes (water mold)	pink rot	*Phytophthora erythroseptica*
	Pythium seed piece decay	*Pythium ultimum*
	Common name	Scientific name
Nematodes	Columbia root-knot nematode	*Meloidogyne chitwoodi*
	northern root-knot nematode	*Meloidogyne hapla*
	pale cyst nematode	*Globodera pallida*
	root-lesion nematode	*Pratylenchus* spp.
	stubby-root nematode	*Paratrichodorus* spp. and *Trichodorus* spp.
Insects	potato tuberworm	*Phthorimaea operculella*
	wireworm	*Limonius* spp., *Ctenicera* spp., *Agriotes* spp.

Overview of Pacific Northwest Potato Cropping Systems

An overview of some characteristics of the major potato production areas in the PNW is provided below, based on Hyrnick and Downey (2007), Stark (2003), and personal communication with extension personnel and industry representatives working in these cropping systems (Chris Benedict, Washington State University [WSU]; Doug Boze, Idaho Crop Improvement Association; Brian Charlton, Oregon State University [OSU]; Kasia Duellman, University of Idaho [UI]; Matt Harris, Washington State Potato Commission; Andy Jensen, Northwest Potato Research Consortium; Don McMoran, WSU; Jeff McMorran, OSU; Jeff Miller, Miller Research Inc.; Nora Olsen, UI; Tom Salaiz, McCain Foods Ltd.; Mike Thornton, UI; Tim Waters, WSU; Carrie Wohleb, WSU; and John Wraspir, Washington State Department of Agriculture).

Idaho

Major production areas in Idaho, from west to east, include: the Treasure Valley, the Magic Valley, southeastern Idaho, and eastern Idaho. Specifics of these production areas are described below. The most frequent cultivars grown in Idaho for processing are: 'Alturas', 'Challenger', 'Clearwater Russet', 'Ranger Russet', 'Russet Burbank', and 'Umatilla Russet'. 'Dark Red Norland' and 'Yukon Gold' are grown in some areas for specialty processing markets. Cultivars grown for fresh pack include 'Red Norland', 'Russet Burbank', 'Russet Norkotah' (various strains), and 'Yukon Gold'. In the Treasure Valley, almost all potatoes are grown for processing, and moving eastward in the state, more fresh pack potatoes are grown. The northern part of the Magic Valley tends to grow a storage crop of potatoes, while the southern portion tends to grow potatoes for direct sale to processors. There is a small pocket of growers in southeastern Idaho who grow chipping cultivars.

The most notable change to potato cropping systems in Idaho in recent years has been expanding amounts of alfalfa and silage corn in the rotations and more growing of potatoes on ground that has received manure applications at some point in the rotation. These changes are due to the increase in dairies in Idaho, particularly in the Magic Valley and the southern part of the Treasure Valley.

Production of seed potatoes in Idaho is concentrated in the eastern and southeastern parts of the state. Seed potato rotations are generally 3 to 4 years in Idaho, with some growers striving for 5-year rotations.

Treasure Valley

The Treasure Valley extends from southwestern Idaho into northeastern Oregon. The Treasure Valley has a longer growing season than other areas of the state and potatoes are typically grown in a 4-to 5-year rotation, with a variety of different rotation crops typically including corn, onions, sugar beets, and wheat. Typically, wheat or corn precede potatoes in the rotation. Some growers have longer rotations that also include alfalfa. Irrigation systems consist of either center pivot or solid set irrigation systems. Verticillium wilt and black dot are the primary soilborne disease problems.

Magic Valley and Southeastern Idaho

The Magic Valley and southeastern Idaho most often have 3- or 4-year rotations, with typical rotations consisting of potato-sugar beet-small grain (3-year) or potato-small grain-sugar beet-small grain (4-year). Besides sugar beet and small grains, other rotation crops include alfalfa, beans, and silage corn. Irrigation systems consist of either center pivot or lateral roll wheel lines, with the former predominating in the Magic Valley and the later more popular in southeastern Idaho. The primary soilborne disease or pathogen problems in this area are Rhizoctonia, black dot, silver scurf, Verticillium wilt, nematodes (and *Tobacco rattle virus*), common scab, powdery scab (and *Potato mop top virus*), pink rot, Pythium, and Fusarium.

Eastern Idaho

In eastern Idaho, 2- or 3-year rotations are common, with small grains (wheat or barley) as the rotation crop. Eastern Idaho has some particularly sandy soils and center pivot is the most common form of irrigation. Green manure crops (oilseed radish and mustard) are more frequently grown in eastern Idaho than in other areas of the state, for reasons related to a lack of options for rotation crops and the need for drought tolerant rotation crops due to lack availability of irrigation water. Pink rot has become an issue in eastern Idaho, presumably due to short rotations.

Oregon

The major potato production regions in Oregon are the Columbia Basin, the Treasure Valley, and the Klamath Basin. Seventy percent of Oregon's potato acreage is under center pivot irrigation systems. The remaining acres are irrigated by furrow, wheel line, and solid set systems. Production of seed potatoes in Oregon takes place in Jefferson, Klamath, Gillian, Morrow, Union, and Baker Counties. Rotations for seed potato production systems are generally 2- to 3-years. The most important soilborne disease/pathogen problems in Oregon seed potato production are common and powdery scab, Columbia root-knot nematode, Verticillium wilt, and Rhizoctonia.

Columbia Basin

In the Columbia Basin of Oregon potatoes are grown on 3- or 4-year rotations, with 3-year rotations being the most common. Rotation crops include alfalfa, beans, carrots, field corn, onions, peas, sweet corn, and wheat. Potatoes often follow field corn in the rotation. Most potatoes are grown for processing, with some fresh pack of russet- and specialty-type potatoes, including little/petite potatoes. Cultivars include 'Alturas', 'Clearwater Russet', 'Russet Norkotah', 'Ranger', 'Russet Burbank', 'Shepody', and 'Umatilla'.

Klamath Basin

In the Klamath Basin, potatoes are typically grown in 3- to 7-year rotations, which include alfalfa, green manures (usually oilseed radish or mustard), and small grains. Unique to this area is "Flood-Fallow" or "Walking Wetlands" program which is carried out in cooperation with U.S. Fish and Wildlife Service and its National Wildlife Refuge System and allows a producer to trade a lease or privately owned land to be flooded for the opportunity to farm on the Klamath Basin National Wildlife Refuge. A significant portion of the organic acreage takes advantage of this program. Most of the potato acreage in the Klamath Basin (55-60%) is in chipping cultivars. 'Dakota Pearl,' 'Lamoka,' and 'Waneta' are grown for export markets. About 10% of Oregon acreage is dedicated to seed potatoes. All remaining acreage is grown for fresh market with about 40% of that in organic certification. 'Russet Norkotah' strains are the primary russet varieties, 'Modoc' (red), 'Elfie' and other European varieties (yellow), with some specialty potatoes grown for the fresh market (e.g., fingerlings, purples) are the remainder. About 40-45% of acreage is on soils with an organic matter content around 1.4% and less, while the remaining acreage is on drained soils (e.g., lake bottoms) with high organic matter content ranging from 6% to 20%. Solid set irrigation is standard in this area. The most problematic soilborne diseases and pathogens in this system are black dot, nematodes (Columbia root-knot, northern root-knot, and stubby-root), powdery scab, tuber black scurf, and Verticillium wilt.

Treasure Valley

Potato systems in the Treasure Valley of Oregon are similar to those described above in the Treasure Valley of Idaho.

Washington

Potatoes are primarily produced in the eastern part of Washington in the Columbia Basin and along the Snake River, where water is available for irrigation. Potatoes are also grown in northwestern Washington, in the Lower Yakima valley and the Kittitas valley. Seed potato production in Washington takes place primarily in Whatcom and Lincoln Counties.

Northern Columbia Basin

In the northern part of the Columbia Basin, potatoes are primarily produced for long term storage. They are most commonly grown on a 3-year rotation, with alfalfa, bean, sweet corn, or onion often preceding potato. An estimated 15% of potato acreage is preceded by a mustard green manure. Cultivars are similar to those grown in Oregon’s Columbia Basin, with the exception of ‘Shepody’, which generally is not grown in the northern Basin. In the northern Basin most soils are sandy loams or loamy sands, with some heavier soils in the Othello area of the northern Basin. Irrigation across the Columbia Basin is almost exclusively center pivot. Soilborne pathogen problems are similar across the Columbia Basin. The primary soilborne pathogens are Columbia root-knot nematode, Verticillium, white mold, and black dot.

Southern Columbia Basin

Practices and cultivars grown in the southern part of Washington’s Columbia Basin are similar to those described above for Oregon’s Columbia Basin. Most processing potatoes grown in the southern Columbia Basin are for fresh delivery (rather than storage). A small number of chipping cultivars are grown in both the northern and southern Columbia Basin of Washington, but acreage accounts only for about 5% of the total. Use of green manure is slightly less prevalent in the southern part of the Columbia Basin than in the northern part with an estimated 10% of potato crops preceded by a mustard green manure.

Northwestern Washington

A small portion of the state's potato crop, mainly fresh market potatoes, is produced in northwest Washington, in Skagit and Snohomish Counties. Fresh market potatoes in this area are usually grown on a 3-year rotation, typically followed with a small grain. Other rotation crops include berries, broccoli, Brussels sprouts, field corn, pumpkins, and vegetable seed crops. About one half of the potatoes grown are red ('Chieftain'), but yellows and whites, and some other specialty potatoes (e.g., purple, fingerlings) are also grown. Silt loam soils are common in the area. Production in northwest Washington relies heavily on precipitation, however supplemental irrigation of potatoes is often applied using big guns and boom carts. Major soilborne disease problems are black dot, Rhizoctonia, silver scurf, and Verticillium wilt. Soils are not typically fumigated prior to potato production in this area. Whatcom County is a major producer of seed potatoes.

Lower Yakima Valley and Kittitas Valley

Other areas of potato production in Washington include the Lower Yakima valley where less than 1,000 acres of potatoes are grown for fresh market and chipping, principally red, yellow, and white varieties. In the Kittitas valley, white potatoes are produced for chipping.

Definition of Soil Health

In the 1990's the terms "soil quality" and "soil health" gained traction as a way to expand the view of soil beyond its role as a medium for delivering plant nutrients. Karlen et al. (1997) defined soil quality as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation." Though often used interchangeably with the term 'soil quality', the term 'soil health' is favored by some researchers and growers because of its emphasis on soil as a dynamic and living system and a corresponding focus on soil biology as a critical component. Doran et al. (1996) defined soil health as "the continued capacity of 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." In the discussion that follows, the term 'soil health' will be used.

The U.S. Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS) has adopted the description of soil health proposed by Doran et al. (1996), further emphasizing the multiple functions of a soil essential to sustaining agricultural production: plant production, nutrient cycling, water storage and availability, and diversity of biological habitats. The USDA-NRCS (2012) has suggested several agronomic principles growers can follow to support soil health: minimize soil disturbance, keep soil covered, maximize the duration of living roots, and maximize diversity of crops within rotation.

Defining the health status of a particular soil depends on understanding that soil is a dynamic and complex interaction among abiotic (physical, chemical, climatic) and biotic (plant, animal, microbial) characteristics of the agroecosystem. Characteristics of healthy agricultural soils are generally considered to include: high levels of crop productivity; the highest levels of organic matter supported by the environment; stable structure; high water-holding capacity, infiltration, and drainage; adequate and accessible supply of nutrients; the presence of beneficial soil organisms within the microbial community; low populations of plant pathogens and pests; minimal erosion; and an ability to quickly recover from stresses. In contrast, soils that are not healthy have properties that limit crop productivity, and are constrained by problems such as erosion, compaction, poor structure, poor water and nutrient retention, and high levels of disease, weed, and pest pressures (Larkin 2015).

Soil health reflects both inherent and dynamic properties and processes occurring within a living medium. Inherent soil health changes little over time and is a function of characteristics such as mineralogy, texture, soil depth and slope which are determined by the parent materials, topography and soil forming processes. Dynamic soil properties can be changed by management practices, including conservation tillage (e.g., reduced, minimum, no-till), amending soils with organic materials (e.g., composts, manures, biochar), reducing losses of crop residues, and using cover crops and mulches (Figure 2). Soil health is important to growers not only because it is critical for successful crop production, but also because of its effect on environmental performance, including beneficial effects on soil erosion, air and water quality, and greenhouse gas relations (Granatstein et al. 2017).

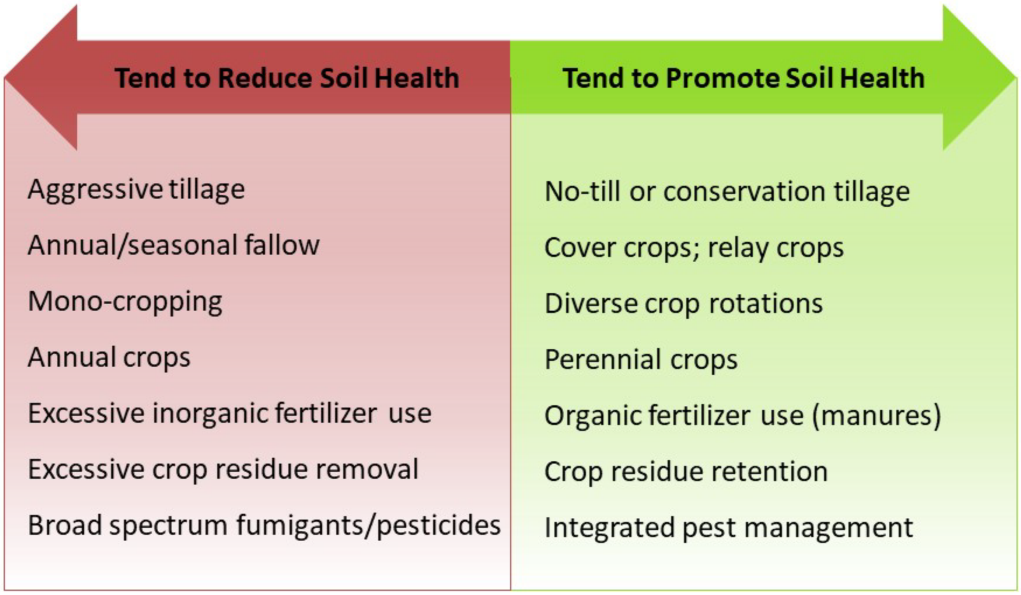

Figure 2. Agricultural management practices and general effects on soil health. (Adapted from Lehman et al. 2015b)

Measurement of Soil Health

Soil Health Indicators

Measuring soil health generally involves the assessment of multiple indicators to create an overall picture of the health of a particular soil. Indicators are linked to specific soil functions (Appendix C) and are usually divided into biological, chemical, and physical components (Table 3). Biological indicators are the most sensitive to management (Nelson et al. 2009) as well as the most complex and the least understood of the three realms (Lehman et al. 2015a).

Table 3. Examples of biological, chemical, and physical properties used in soil health assessment. See Appendix C for a table relating indicators to soil function. (Adapted from Awale et al. 2017)

Biological	Chemical	Physical
✓ Soil respiration ✓ Potential mineralizable nitrogen ✓ Microbial biomass ✓ Soil enzymes ✓ Earthworms ✓ Crop condition, root growth ✓ Weed, pathogen, and soil insect pressure	✓ Organic C and N ✓ Particulate organic matter ✓ Active carbon ✓ pH ✓ Cation exchange capacity and base saturation ✓ Electric conductivity ✓ Heavy metals	✓ Soil color ✓ Aggregate stability ✓ Water infiltration ✓ Bulk density ✓ Penetration resistance ✓ Water-holding capacity ✓ Runoff and erosion ✓ Rooting depth

Diversity, abundance, and metabolic activity of soil microbial communities can be used to quantify of a soil's health (Ferris and Tuomisto 2015). In the past, understanding of microbial communities in soil has been constrained by the inability to culture many soil microbes in the laboratory. The development of culture-free methods (e.g., molecular genetic approaches) is making it more feasible to quantify the diversity and abundance of soil microbial communities as well as to quantify specific members of the soil microbial community, including soilborne plant pathogens. The study of soil microbial communities is an active and growing area of research that may yield additional perspectives on soil, root, and potato tuber health. However, because significant uncertainty exists regarding the totality of functions of microbial communities in soil, results from molecular genetic approaches aimed at understanding the soil microbiome as a whole are not always readily translated to practical strategies for modifying soil management practices. For this reason, and because molecular genetic approaches to characterize an entire microbial community are costly, these techniques are usually employed for answering targeted research questions. In contrast, biological indicators of soil health often focus on a proxy measurement (e.g., microbial biomass, respiration, enzyme activity) or the measurement of some fraction of soil organic matter, rather than measuring a microbial community directly.

Soil organic matter levels change slowly and are affected by factors such as initial levels of soil organic matter, duration of management change(s), and soil and environmental conditions. Thus, it is often useful to measure specific fractions of soil organic matter that are most sensitive to management (e.g., active carbon or other fractions), in order to assess soil organic matter changes and future trends. Descriptions of many of these fractions of soil organic matter and research results from PNW grain systems are presented in Awale et al. 2017. Gregorich et al. (1997) suggested that soil organic matter, particulate organic matter (defined as organic matter between 0.053 mm and 2 mm in size), and microbial biomass were useful indicators to track changes in soil health for agricultural soils, in general.

A major challenge of soil health research and assessment is the lack of a standard set of soil health indicators that are reliably sensitive to changes in crop management and which are also cheap and accessible (Awale et al. 2017). It is unlikely that any one set of indicators would apply to all soil and cropping system situations, and thus the use of a minimum set of indicators has been suggested as an alternative. Though offering testing for soil health indicators is becoming increasingly common for soil testing laboratories, there is not complete agreement regarding which indicators are most important. In September 2018, USDA-NRCS released for public comment a draft Technical Note for Soil Health, describing recommended soil health indicators and associated laboratory procedures (USDA-NRCS 2018). The selection of indicators can have an important effect on results. The Soil Health Institute developed a list of 19 indicators most useful for measuring soil health.

Soil Health Assessments

Several assessments of soil health have been developed in recent years that use specific indicators of soil health and combine them into indices to “score” a soil’s health status. Generally, the most useful indices are those that include a myriad of soil health indicators (Bastida et al. 2008). The calculation of an index generally has three steps: (1) identification of indicators based on management goals, (2) indicator interpretation or scoring, and (3) integration of all indicator scores into a comprehensive soil health score (Awale et al. 2017).

The Soil Management Assessment Framework (Andrews et al. 2004) was developed by the USDA Agricultural Research Service (ARS) and the USDA-NRCS as an approach to indicator selection, interpretation, and integration into an index, that is transferable to a variety of soil types, climates, and soil management systems. Since the assessment of soil health is site- and soil-specific, the Soil Management Assessment Framework tool allows the user to manipulate factors such as inherent soil characteristics, environmental influences such as climate, and human values such as intended land use, management goals, and environmental protection (USDA-NRCS, in preparation).

One common assessment tool is the Comprehensive Assessment of Soil Health (formerly known as the Cornell Soil Health Test), released in 2006, which was developed as a commercial-scale user-friendly soil health test for land managers (Moebius-Clune et al. 2016). Though results are normalized and scored based on results from soils in the northeastern U.S., the test may be useful in the PNW for comparing two soils in the same area under different management or for monitoring changes in soil health at a single site over time. For assessment tools to be useful for growers in rating the health of a soil, there must be an understanding of the range of values present within a specific geographic area. For example, a soil considered healthy in an arid or semi-arid climate may be scored very differently than a healthy soil in a high rainfall area due to inherent differences in these soils.

In the PNW region, the Oregon State University Soil Health Test is being developed based on the Cornell test. Samples were collected throughout Oregon during 2017 and 2018 using paired “treatments” on similar soil types (e.g., conventional vs. organic management, or differences in tillage, cover cropping, or crop rotations). The resulting data will be used to help hone the scoring system for Oregon (Andrews et al. 2017, 2018). The OSU group is also working on repeatability of soil health metrics, comparing different methods for assessing availability of organic nitrogen (e.g., potentially mineralizable nitrogen [7 day and 28 day], autoclaved-citrate extractable protein – a measure of potentially available organic nitrogen, hot potassium chloride extraction), grouping assessments by specific soil function, and building a PNW database. In the future, OSU may offer “bundles” of tests aimed at certain soil functions (e.g., nutrient cycling, habitat, soilborne disease suppression) (Andrews, personal communication).

The Haney Soil Health Index (Haney 2014), more recently called The Soil Health Tool (Haney et al. 2018) utilizes three different measures of active organic soil carbon fractions (mineralized carbon, water extractable organic carbon, and water extractable organic nitrogen). The Haney Soil Health Index tries to account for nutrients that are available later in the season (in addition to nutrients available at the time of sampling, as measured by standard chemical soil tests) and results in a soil health score that can be used to quantify soil health. However, researchers in the PNW have identified some potential issues related to the applicability of this method in the West, as discussed in the following section.

Usefulness of Soil Health Indicators

Without a baseline understanding of the average values for indicators in an area or for a specific type of soil, soil health measurements have little value. For any soil health indicators to be useful, there generally needs to be a comparison made. A pasture or a native system (not converted to agriculture) is sometimes used as a reference point for soil health. Alternatively, test results can offer a baseline to which changes over time are compared (Granatstein et al. 2017). Fields under contrasting soil management may also be usefully compared in many cases. As with any type of soil testing, the key to a test's usefulness for growers is the correct interpretation of the test results and an understanding of how any indicator relates to actual soil problems, crop yield, and quality. It is also worth noting that while decades of work by agricultural researchers has gone into the interpretation of chemical soil test results to providing regionally-appropriate nutrient recommendations, similar work has not occurred for biological and physical indicators of soil health.

Region-Specific Information on Soil Health

The soils in the western U.S. are much different than those soils in the eastern U.S. where the concept of soil quality (and soil health) was initially developed in the U.S. For example, in the Columbia Basin of Washington and Oregon, irrigated agricultural land has undergone conversion from the native semi-arid shrub-steppe ecosystem, which receives a low amount of precipitation and has low amounts of carbon added to the soil. Soils in the Columbia Basin thus started with low levels of organic matter in their native form (less than 1%), and irrigation and high residue cropping systems in some rotations has actually *increased* levels of organic matter (Cochran et al. 2007). This situation contrasts to soils in areas of high rainfall, for which intensive agriculture has resulted in *decreased* levels of organic matter. Despite the increase in soil organic matter brought about by agricultural management and the high yields of potatoes and other crops (and thus higher levels of residue inputs) in the Columbia Basin area, the inherently low levels of organic matter present in this system would not qualify it as "healthy" by standards based on soils in the Northeast or Midwest.

Some work has been done to examine the usefulness of specific soil health indicators across geographic regions. Fine et al. (2017) analyzed a database of soil samples from three regions of the U.S. (Northeast, Mid-Atlantic, and Midwest) and found that active carbon was the indicator that accounted for 45% of the variation between samples. Three additional indicators (penetration resistance, respiration, and wet aggregate stability) were suggested for inclusion in a simplified soil health test. Soils in the arid/semi-arid West were not included in this study and, for reasons stated above, these soils are not comparable to those in the eastern and midwestern U.S.

The Haney Soil Health Index (and possibly other soil health tests) may overemphasize the importance of carbon levels in the soil, while not considering the effects of other factors, such as soil salinity or sodicity (sodium level), important to crop yield and quality in the inland PNW (A. Leytem, personal communication; Moore et al. 2016b). The Haney Soil Health Index may require further calibration to be useful for this area as it is not highly sensitive to changes in tillage or cropping practices in the region (Morrow et al. 2016), either.

In contrast, the Comprehensive Assessment of Soil Health, the Soil Management Assessment Framework, and the NRCS Soil Health Assessment focus on multiple soil properties, including chemical and physical properties and have been used across a diverse array of soils and management practices. Awale et al. (2017) report that although their use in the inland PNW has been scarce, it appears that they could be effectively used to monitor soil health in dryland cropping systems.

There have been limited efforts to assess the most suitable soil health indicators for use in the semi-arid West. Morrow et al. (2016) measured soil organic matter properties including soil organic carbon, total N, acid nonhydrolyzable carbon, acid nonhydrolyzable nitrogen, acid-hydrolysable carbon, acid-hydrolysable nitrogen, microbial biomass carbon, microbial biomass nitrogen, carbon mineralization, permanganate oxidizable carbon, ion exchange membrane nitrogen, and potential nitrogen mineralization. These properties were measured at five long-term field experiments across the inland PNW in both dryland and irrigated cropping regions involving tillage and crop intensification (fallow reduction) treatments. The authors used the following seven criteria to judge soil health metrics: (1) evidence based, (2) sensitive to change,

(3) logistically feasible—they can be conducted within the time constraints of effective decision making, (4) cost effective, (5) accurate and precise, (6) performed *in situ* or on relatively undisturbed samples—capturing real world conditions, and (7) valued —they provide relevant, interpretable, timely information that enables sound management decisions. Of the properties measured, permanganate oxidizable carbon (active carbon) scored the highest using these criteria.

Andrews et al. (2004) evaluated the utility of the Soil Management Assessment Framework for comparing soil health across dryland small grain systems, and similar work to evaluate the effectiveness of this or other assessment tools in PNW potato systems would help a range of stakeholders better understand their potential utility.

Hurisso et al. (2016) examined two different measurements of active organic matter, permanganate oxidizable carbon and mineralizable carbon, to determine the function of these two indicators over a wide range of soil types, geographic areas, and crop management histories represented by 13 studies over 76 sites in the U.S. None of these sites were in the PNW, but some did represent irrigated agriculture in the central valley of California. In this study, Hurisso et al. found that permanganate oxidizable carbon better reflected practices that promote organic matter accumulation or stabilization, while mineralizable carbon better reflected practices that promote organic matter mineralization, and, thus, the latter can be a useful predictor of short term nutrient availability. Both indicators were better predictors of crop productivity than other fractions of soil carbon (total soil organic carbon, microbial biomass carbon, or particulate organic matter carbon).

The suitability of different soil health indicators and assessments for use in the PNW is now an area of active research. One example is a project currently being conducted by Andrew McGuire at WSU’s Center for Sustaining Agriculture and Natural Resources and WSU Extension. The project is funded by the Washington State Soil Health Committee (“Health Monitoring Sites in Irrigated Eastern Washington”). This project has the goal of using a few proven indicators – total soil organic matter, active carbon, and respiration (Hurisso et al. 2016) – to evaluate the range of soil health on irrigated farms in eastern Washington and to document the potential benefits of soil building practices, such as cover crops, organic amendments, and high-residue farming.

Though its primary focus is dryland grain systems, a chapter on soil health in a recently published book titled Advances in Dryland Farming in the Inland Pacific Northwest offers a helpful overview of the topic of soil health and regional research results in grain systems (Yorgey and Kruger 2017).

Soil Health Challenges Specific to Potato Systems in the PNW

The challenges of improving soil health in potato systems in the PNW include

- the intensive cultivation that is generally used in potato systems;
- the importance of tuber quality that can be compromised by soilborne pathogens, especially plant-parasitic nematodes;
- the small amount of crop residue left on the fields after harvest;
- the fact that late harvest of late maturing potato varieties may prevent adequate establishment of cover crops after potatoes;
- the risk of compaction when equipment is driven on wet fields (especially in areas west of the Cascades); and
- the shorter and shorter rotations which exacerbate soilborne disease problems and lead to a reliance on soil fumigation in some cases.

The industry would like to increase future potato production in the region. However, expansion in many potato production areas of the PNW is limited by access to irrigation water. The remaining options are either to increase potato yield per acre or decrease the length of rotations. The latter especially, would be a challenge from a soil health perspective if additional crop management practices were not also implemented.

In the Columbia Basin in particular, and to some extent in other areas of the inland PNW, raising levels of soil organic matter has been considered difficult due to the well aerated soils with low clay content, hot climate, and intensive tillage. In many parts of the PNW, land is farmed under short term leases, so potato growers may have less motivation to improve the soil and may have little control over parts of the rotation.

The extent to which soil health can be improved within the productivity and profitability constraints of the current high input and intensive management regime of potato production is not clear. Additional barriers exist in some cases due to the requirements of potato processor operations. As an example: from 2004-2009 a study was conducted in the southern Columbia Basin on a Quincy sand, investigating reduced tillage in the potato production year and no-tillage of corn during rotation years (Collins et al. 2010). Reduced tillage rotations maintained potato yields compared to conventional tillage rotations and improved soil organic matter, but corn residues that remained in the field during potato harvest potentially could have posed a problem during processing, as harvested tubers were contaminated with corn stover (Collins et al. 2010). Addressing these types of issues, and avoiding other unintended consequences, is vital to the adoption of strategies to improve soil health.

While there are certainly barriers that exist, the industry is always evolving and pressures such as changing consumer preferences, grower audits, and regulations surrounding fumigation are compelling the potato industry to look for new management strategies, including options for improving soil health. An additional factor that is changing the landscape around management is climate change, which is expected to affect the geographic ranges of specific species of insects and diseases for a given crop-growing region (Porter et al. 2014). In response to climate change, many species have extended their ranges toward the poles, or developed or reproduced earlier in the spring than previously (Bradshaw and Holzapfel 2006; Parmesan and Yohe 2003). For example, climate change is predicted to result in a continued range expansion for potato tuberworm in temperate production areas, such as the Pacific Northwest (Kroschel et al. 2013). These factors, and other predictable and unpredictable future changes must be considered when assessing the larger picture that may impact adoption of strategies for soil health improvement.

Approaches to Improving Soil Health in Potato Systems

While the literature does not provide a simple straightforward approach to improving soil health in PNW potato systems, the results of studies on specific practices that have been used in potato systems in the PNW and elsewhere can inform an overall effort to improve soil health in these systems. The following sections summarize existing research on the topics of: reducing tillage; crop rotation; reducing use of soil fumigants and other agricultural chemicals; use of cover crops and green manures; use of animal manures, composts and alternative fertilizers; and use of microbial inoculants. Within each topic, the current state of these practices in PNW potato systems, results from relevant literature detailing how these practices relate to soil health in potato systems, and, where available, the economic implications of adopting these practices are described. The impact of potato breeding and seed potato production as they relate to management of soilborne disease is also is discussed.

Reduced Tillage

Wind and water erosion have caused dramatic declines in soil productivity worldwide (Pimentel 2006), with soil losses in the U.S. exceeding 3 billion tons annually (O'Geen and Schwankl 2006). Erosion protection and associated conservation of nutrients, organic matter, soil water holding capacity, and health of the soil microbial community are therefore important concerns. Wind erosion is a serious problem in many potato production areas in the arid and semi-arid West and can damage young plants plus have negative effects on fertility, soil structure, tilth, infiltration, and water holding capacity (McGuire 2011). The cultivation, hilling, reservoir tillage (dammer-diking) and harvesting practices for potato production can increase soil erosion (Auerswald et al. 2006; Ruysschaert et al. 2006), injure potatoes, increase soil compaction (Perrone and Madramootoo 1994) and bring weed seeds to the soil surface (Eberlein et al. 1997).

Conservation tillage consists of a range of tillage practices that are designed to reduce soil degradation and soil erosion (Carter et al. 2007). A reduction in tillage minimizes soil disturbance, changes the distribution of crop residues, and alters their decomposition rate, resulting in changes in soil properties, biological activity and soil organic matter, all of which have the potential to influence crop yield and soil health (Paustian et al. 1997). Growers that have implemented conservation tillage generally do so for two basic reasons: (1) to improve soil and water conservation, and (2) to reduce costly inputs and increase profits. Limitations to adoption of conservation tillage in many cropping systems have included poor crop stands due to cool soils, disease and pest problems, along with poor soil-seed contact; poor weed control; inability to manage crop residues; inability to incorporate fertilizers and pesticides; and, cost to replace existing equipment.

A number of successful conservation tillage approaches have been developed for small grain and forage production systems, but few have been developed for potato production systems. Success of conservation tillage in potato production systems is dependent on adoption of effective weed control strategies, modifications to nutrient delivery, and pest and disease management (Morse 1999).

In potato production, tillage is primarily used to control weeds, facilitate planting, control water runoff, and increase the ease of later cultivation and harvest (Carter et al. 2007; Eberlein et al. 1997; Hoyt and Monks 1996). While the exact timing of tillage operations varies within different areas of the region, the following mechanical field operations typically occur in PNW potato production systems. After straw from a preceding grain crop is removed, fields are disked and, on occasion, subsoiled with long shanks (deep ripped)to break up compaction layers. Prior to spring planting, fields are prepared with chisel or moldboard plowing followed by shallow disking, and 25-30 cm tall hills are formed at planting to promote an environment conducive for tuber development. Fields are cultivated and hilled once early in the growing season for weed control, water penetration, and to prevent tuber greening. A dammer-diker is used to create a depression between rows. This type of reservoir tillage is used to prevent runoff and promote uniform water infiltration. Potato vines are chopped or rolled and usually sprayed with a chemical desiccant in the fall prior to harvest to ensure skin set. At harvest, a potato digger is used to lift the tubers from about a 30 cm depth depending on the cultivar. Adopting conservation tillage to reduce erosion, increase nitrogen use efficiency, and build organic matter would improve soil health and environmental quality of irrigated potato production systems.

Reduced tillage has had limited testing in potato production, primarily in rainfed areas of North America or Europe (Auerswald et al. 2006; Carter and Sanderson 2001; Hoyt and Monks 1996; Liebman et al. 1996; Mundy et al. 1999; Pierce and Burpee 1995; Ruysschaert et al. 2006). Testing has been even more incomplete in systems with center pivot irrigation. Commercial potato planters, hilling equipment, and reservoir tillage equipment are not designed to handle large amounts of crop residues. Hyde et al. (1974) in the PNW modified a potato planter to be capable of handling large amounts of residue that resulted in less soil disturbance during planting. The authors reported that problems encountered during harvest ranged from none to severe depending on the amount of residue, and the time between planting and harvest. Early harvests had surplus non-decomposed residues that caused harvesting problems, while there were few problems with late harvested potatoes. Yields of reduced tillage potatoes ranged from 24-30 tons/ acre and equaled or exceeded yields of conventionally planted potatoes in the Hyde et al. study.

Collins et al. (2010) conducted research on reduced tillage in a 3-year potato rotation (potato-sweet corn-sweet corn) at the USDA-ARS Integrated Cropping Systems Research Farm near Paterson, Washington. Results from six years of production showed that reduced tillage did not significantly affect potato yield or quality. The primary pieces of equipment used in the operations were: flail chopper, Sunflower™-chisel-chopper-packer, 13 shank mark-out implement, and potato planter. Compared to conventional potato systems that leave little crop residue on the soil surface, this approach maximized residue retention (Figures 3, 4). Within the reduced tillage potato, the majority of soil disturbance resulted from planting, hill formation, reservoir tillage, and at harvest from the digging operation. The approach reduced the total number of soil disturbance operations to four, including harvest, compared to the seven soil disturbance operations used in the conventionally tilled treatments (Table 4).

Figure 3. Potato hills formed under reduced tillage in corn residues at the field site near Paterson, Washington. (Source: Collins et al. 2010)

Conventional Reduced

Figure 4. Conventional and reduced tillage plots at the field site near Paterson, Washington. (Source: Collins et al. 2010)

Collins et al. observed soil protection by crop residues in reduced tillage plots after a wind storm following emergence. Note the shifting of hills in conventional tillage vs. the integrity of the hills in reduced tillage (Figure 4). Potato plants were damaged by the blowing sand in the conventional tilled but recovered, with minimal damage observed in the reduced tillage plots.

There was no significant difference in potato yields between the conventional and reduced tillage treatments (Table 5). Economic analyses of the reduced tillage system showed returns over total costs for the potato year of the rotation of $2,477 per acre in the reduced tillage system compared to $2,421 per acre for the conventional tillage system. Over the whole rotation, returns were $803 per acre for the reduced tillage system and $812 per acre for the conventional tillage system (Painter 2009a, 2009b).

Table 4. Field operations and equipment used in tillage trials at Paterson, WA. Trials conducted in a three year rotation (sweet corn/ sweet corn/ potato).

Potato	Operation	Conventional tilled	Reduced till
	Residue Management	Flail chop corn residues	Flail chop corn residues
	Pre-plant fertilization	Valmar™ spreader, (100 lbs N, 29.5 lbs P, 98.4 lbs K)	Valmar™ spreader, (100 lbs N, 29.5 lbs P, 98.4 lbs K)
	Primary tillage	2 passes JD8760™ & 13' Sunflower™ chisel/ chopper/packer	**None**
	Mark-out	13-shank bed splitter	13-shank bed splitter
	Plant	6-row Harriston™ pick planter	6-row Harriston™ pick planter
	Drag-off	6-row rodweeder	**None**
	Dammer dike	Dammer diker	Dammer diker
	Harvest	3-row potato digger	3-row potato digger
Sweet Corn yr 1 and 2			
	Pre-plant fertilization	Valmar™ spreader (48 lbs N/A, 48 lbs P, 54 lbs S, 0.95 lbs B)	Valmar™ spreader (48 lbs N/A, 48 lbs P, 54 lbs S, 0.95 lbs B)
	Primary tillage	2 passes JD 8760™ & 13' Sunflower™/packer.	**None**
	Plant	12-row John Deere/Orthmann™ Minimum Tillage planter UN32 applied at-plant at 10.3 gpa (36 lbs N/A).	12-row John Deere/Orthmann™ Minimum Tillage planter UN32 applied at-plant at 10.3 gpa (36 lbs N/A).
	Harvest		

In season fertilizer applied through center pivot.

Table 5. Potato yields from conventional and reduced tillage treatments during 2004-2009, under centerpivot irrigation, USDA-ARS-ICRF, Paterson,Washington. (Adapted from Collins et al. 2010)

Year	Conventional tillage	Reduced tillage
	------ T/acre -----	
2004	37.8	37.0
2005	37.7	38.6
2006	36.3	36.1
2007	30.9	29.8
2008	40.9	39.7
2009	40.1	37.9
Average	**37.2**	**36.4**
Standard deviation	**3.9**	**3.9**

Sharratt and Collins (2018) reported the potential of wind erosion from the same study. Sediment flux was measured inside a portable wind tunnel after primary tillage of potato in autumn 2009 and after sowing potato and corn in spring 2010. Soil loss was significantly greater from potato than first or second year corn in autumn 2009. It was also significantly greater from conventional compared to reduced tillage in spring 2010. Simulations by a Wind Erosion Prediction System indicated that most of the erosion over the 3-year rotation occurred between harvest of potato in September and the following March. Differences in soil loss among crop treatments or between tillage practices were due to differences in residue cover. Since wind erosion was most apparent from conventional tillage and after harvest of potato, the authors recommended that cover crops should be established soon after potato harvest in conventionally tilled fields or reduced tillage practices be adopted to protect the soil from wind erosion in the Columbia Basin.

Understanding how potatoes and soils respond to changes in tillage management requires an assessment of changes in key physical, chemical and biological soil properties (Carter et al., 2007). Soil organic matter, microbial diversity, and microbial biomass and activity are known to increase more in the surface layer of soils under reduced tillage than under conventional inversion tillage (Honeycutt et al. 1995; Paustian et al. 1997). Tillage affects the amount of soil organic matter buildup in two fundamental ways, (1) through the physical disturbance and mixing of soil and the exposure of soil aggregates to disruptive forces and (2) through controlling the incorporation and distribution of plant residues in the soil profile.

Organic carbon and nitrogen concentrations and microbial biomass and activity are known to increase in the surface layer of soils under reduced tillage more than under conventional tillage (Paustian et al. 1997). Differences in soil organic matter between no-tillage and conventional tillage are most extreme near the soil surface, primarily due to differences in the distribution of residue inputs. Eighteen years of cultivation in potato-based rotations that included corn and wheat in rotation prior showed little to no change in soil organic matter at the Paterson field site. The reduction of tillage in the 3-year potato rotation showed no significant differences in any of the chemical or biological parameters measured. The lack of significant soil organic matter buildup under reduced tillage is likely a characteristic of the Quincy sand soil type and environmental conditions of the Columbia Basin. Characteristics of this soil include a high sand content (92%), lack of soil aggregation, a high decomposition rate of residues due to application of irrigation water, and a high mean annual soil temperature of 53^{o}F relative to other regions. Alva et al. (2002) reported that 85-90% of potato and corn residues incorporated in the surface 0-30 cm of the Quincy sand soil were lost between the months of January and September. These conditions limit carbon accumulation even under reduced tillage in this soil.

In other regions, Carter and Sanderson (2001) found that soil organic carbon increased 17% after 6 years of reduced tillage in a 3-year potato rotation in eastern Canada. The Canadian Charlottetown fine sandy loam soil contained 54%, 29%, and 17% of sand, silt and clay, respectively, and had a high degree of water stable aggregates. Therefore, additions of residues alone do not determine the potential for carbon sequestration. Soil physical properties of texture and aggregation are also important. Physical protection through aggregation, accumulation of particulate organic matter and the light fraction and interactions with soil primary particles provides the formation of stable soil organic matter.

Collins et al. (2010) further explained that increased residues and organic matter levels and higher optimal water status under irrigation, resulted in greater microbial biomass in the surface of reduced tillage soils and is associated with greater reserves of potentially mineralizable nitrogen, a measure of nitrogen that may be converted to plant-available forms. The mineralized nitrogen results from conversion of soil organic matter nitrogen by the soil microbial community. In the reduced tillage study (Collins et al. 2010), the nitrogen mineralized in the surface 8 inches of soil was 28, 30, and 40 lbs nitrogen/acre for potato, first year sweet corn and second year sweet corn, respectively, regardless of tillage method. These values are similar to data reported by Alva et al. (2002) in a study evaluating crop residue decomposition within a potato rotation in the Columbia Basin. They found that mineralized nitrogen amounts in the field from corn, wheat and potato residues during May through September were 29, 46, and 22 lbs/acre, respectively.

The effect of minimum tillage potato production on disease incidence in the PNW potato production is not well understood. Collins et al. found that *Pythium* spp., *Fusarium* spp., and *V. dahliae* populations declined over 3 years of the reduced tillage potato-sweet corn-sweet corn rotation described above (Collins et al., unpublished data). In Prince Edward Island, Peters et al. (2008) compared incidence of silver scurf, Rhizoctonia, dry rot, and common scab in conventional and minimum tillage 2- and 3-year potato rotations and found that minimizing tillage seemed to pose no constraints to crop health in 3-year rotations. Understanding the effect of reduced tillage on the major pathogens of PNW potato production will be critical information to have in considering the adoption of this practice.

Crop Rotation

Crop rotation is used for multiple purposes in potato production including disease and pest management, soil fertility, and soil improvement. In general, the longer the rotation, the greater the benefits to the following potato crop, as the potato year in a rotation sequence can have significant negative impacts on soil biological properties (Nelson et al. 2009), soil physical properties (Edwards 1988), and soil health (Boiteau et al. 2014). Potato rotations vary widely across the PNW and may include rotational crops such as alfalfa, canola, dry beans, field corn, grasses, green manures, peas, small grains, sugar beets, sweet corn, and vegetable crops. Typical rotation lengths and rotation crops in the region are discussed in the section above titled Overview of Pacific Northwest Potato Cropping Systems. Many potato production systems involve relatively short rotations (two to three years) due to the economics of production. Constraints on available land often drive growers to adopt shorter rotations in an effort to balance risks and returns (Myers et al. 2008). In some cases, the yield benefit from extending the rotation may make up for the cost of growing the most profitable crop less frequently. Research conducted during 1995 and 1996 in 45 eastern Idaho fields showed that average yields for 3-year wheat-wheat-potato rotations were usually about 30-40 cwt per acre higher than for 2-year wheat-potato rotations (Stark 2003).

Crop choices for inclusion in a potato rotation and the management of that crop can have important impacts on soil health. From a soil health perspective, including crops that involve minimal tillage (such as no-till corn or perennial forage crops) and crops that produce residue left on the field, plus including crops having different root architectures (e.g., cereals with fibrous root systems to break up compacted soil), offer opportunities for soil health improvement during the non-potato portions of the rotation. Rotating potatoes with several years of alfalfa is a widely used practice for providing nitrogen in organic potato production in the PNW. It is estimated that an alfalfa stand and existing soil organic matter can contribute between 150 and 240 lbs nitrogen per acre to crops following in the rotation (Westerman and Crothers 1993).

Shiffler and Hopkins (2009) compared soil and crop parameters from 27 pairs of fields that had either short (average of 2-year) or long (average of 4-year) rotations in the Snake River Valley of Idaho and the Columbia Basin of Washington. While the incidence and severity of Verticillium wilt was greater in the short rotation fields, there was no difference found between short and long rotations in terms of soil carbon, mineral nutrients, bulk density, aggregate stability, or water infiltration. In a greenhouse container study, potatoes grown in soil from short rotations began senescence an average of 15 days earlier and produced 19.6% less tuber yield. The authors determined when long-term impacts are factored in, the costs of short rotations is much higher than what they may appear initially. A survey of PNW growers showed that as of 2009, growers representing over 59,203 acres had added at least one year to the length of their potato rotation as a direct result of this project.

While rotation rarely eliminates soilborne pathogens completely, it can be effective at reducing numbers of some organisms. For each pest or disease of concern, it is important to understand the host status of cash and cover crops included in the rotation, the host status of weeds present, and the organisms' ability to survive in soil, in the absence of a susceptible host. In the case of some diseases, it may also be important to understand the interaction between a specific isolate of the disease and specific cultivars of rotation crops. For example, it is important to differentiate between vegetative compatibility groups (VCG) of *V. dahliae,* since VCG4A is the one that is highly aggressive to potatoes (Omer et al. 2008). The effect of crop rotation on common soilborne diseases, nematodes, and insects are discussed below.

The pathogen causing black dot has a wide host range including members of 17 plant families primarily in Cucurbitaceae, Fabaceae, and Solanaceae, and disease severity increases with plant stress including over irrigation, blowing sand, or Verticillium wilt (Johnson et al. 2018). Nitzan et al. (2006) found that yellow mustard grown in rotation with potatoes had a 59% incidence of colonization by black dot; alfalfa had an 11% incidence, and wheat, corn, rye and barley had no colonization. Johnson and Cummings (2015) found that incidence of black dot significantly decreased as the number of years out of potatoes increased from three to five years, and beyond, and increased with the number of previous potato crops up to 16. According to Johnson and Cummings, five or more years out of potato are necessary to appreciably affect soil inoculum levels of black dot.

The pathogen causing common scab can survive in the soil as a saprophyte or by infecting other crops, including other fleshy root vegetables (e.g., beet, radish, carrot, and turnip). However, crop rotation can play a role in managing inoculum level in the soil. Rotation with small grains or alfalfa tends to decrease severity in subsequent potato crops (Wharton et al. 2007). Pink rot inoculum in the soil can be reduced by a 3- to 4-year rotation (Secor and Gudmestad 1999) including a legume (Wharton and Kirk 2007). Fields with powdery scab should rotate out of potato for at least five years (Falloon 2008). A 3- to 4-year crop rotation also helps with Rhizoctonia, with preferred rotation crops including barley and oats, but sugar beets and dry beans should be avoided as they are alternate hosts for Rhizoctonia (Secor and Gudmestad 1999). There are no alternate hosts for the pathogen causing silver scurf, which is primarily a seedborne disease, however, it can survive as a saprophyte on dead leaf tissue from alfalfa, sorghum, rye, oats, maize, wheat, rapeseed, red clover and buckwheat (Mérida and Loria 1994) and very few fungicides are effective in controlling it (Errampalli et al. 2001). In the Johnson and Cummings (2015) study, the incidence of silver scurf was greatest in fields out of potato only one year and increased as the number of previous potato crops increased. It was expected that when fields had been rotated out of potato for three years or more, any silver scurf present was due to infected seed.

Verticillium wilt is the major component potato early dying (PED) complex, which in PNW production systems involves *V. dahliae*. Though soil fumigation can offer effective control of *V. dahliae* for the following season, it kills only a portion of the microsclerotia and surviving microsclerotia can infect subsequent crops (Johnson and Dung 2010). Though a number of crops regularly used in rotation with potato are not susceptible to Verticillium wilt (e.g., alfalfa, wheat, sweet corn), the inoculum levels in a field can remain high despite rotation with non-host crops. For these reasons, crop rotation is not considered to be an effective strategy for management of *V. dahliae* (Rowe and Powelson 2002). In a study from the Columbia Basin, where fumigation is regularly used to control Verticillium wilt, the number of years out of potato (2-6 years) did not have a significant effect on potato yield (Dung et al. 2015). The rotation crop immediately preceding the crop and the number of years in mint production (also a host for *V. dahliae*) also had no significant effect on yield (Dung et al. 2015) .

Rotation crops can be important to consider in the control of some nematodes, but not others. Some crops commonly used in rotation with potatoes (e.g., alfalfa, field corn, wheat) actually increase populations of Columbia root-knot nematode (Ingham et al. 1999). Ingham et al. (1999) reported that two years of a non-host summer crop and a rapeseed cover crop preceding potato has been shown to reduce Columbia root-knot nematode populations to 0-1 juveniles per 250 g soil in the Columbia Basin. The order of cropping sequence can be important too. According to Ingham (2017), when using crop rotation to control Columbia root-knot nematode, cropping sequences should be designed to grow the best host crops early in the rotation (just after potatoes) reducing the subsequent population increase with poor or non-hosts later.

Pale cyst nematode, a type of potato cyst nematode, was first discovered in southeastern Idaho in 2006 and poses a serious threat to potato production. Cysts of the pale cyst nematode can stay dormant in soil for 30 years in the absence of a host, with eggs inside remaining viable, making crop rotation an ineffective strategy. Because of the serious threat posed by this organism, USDA's Animal and Plant Health Inspection Service (APHIS) has actively worked to prevent the spread of pale cyst nematode from the areas where it's been found in Idaho (USDA 2015).

The root-lesion nematode includes several species. One of particular concern in the PNW is *Pratylenchus penetrans*, which can have a synergistic interaction with *V. dahliae*, intensifying disease severity (Botseas and Rowe 1994). LaMondia (2006) found that populations of *P. penetrans* may be reduced by one or two years of rotation to a non-host crop, reducing the severity of potato early dying complex, despite the persistence of *V. dahliae* microsclerotia in the soil.

Stubby-root nematodes cause little direct damage to potatoes, but are the vector for *Tobacco rattle virus*, which causes corky ringspot in potatoes. Stubby root nematodes have a wide host range of crops and weeds so they are difficult to control with crop rotation. Alfalfa is a non-host for stubby-root nematode. Their migration in the soil profile makes fumigant nematicides an ineffective choice for controlling stubby-root nematodes (Hafez and Sundararaj 2009).

Though soil insect pests are not extensively addressed in this paper, it is worth noting two insect pests that spend a portion of their life cycles in the soil: potato tuberworm and wireworm. In the case of potato tuberworm, crop rotation is not an effective method of cultural control (Rondon et al. 2007). Crop rotation is, however, an important tool for controlling wireworms. Populations of wireworms affecting potatoes tend to increase following clover or small grains (PNW Pest Management Handbook).

Reducing Use of Soil Fumigants and Other Agricultural Chemicals

The soil fumigant sodium N-methyldithiocarbamate (metam sodium; trade names: Metam CLR, Sectagon, and Vapam) is routinely used in potatoes and is considered necessary by most growers to control potato early dying, especially when populations of *V. dahliae* are above a threshold of 10 colony forming units (CFU)/g soil (K. Frost, personal communication) and when rotations are less than three years (McGuire 2003). Metam sodium is also used for nematode control but is considered less effective than 1,3-dichloropropene (1,3-D, trade name Telone II) (M. Thornton, personal communication). In 2006, fumigation was used on 90% of Washington potato acres, 82% of Oregon potato acres, and 50% of Idaho potato acres (Hirnyck and Downey 2007).

Interest exists in alternatives to chemical fumigation because of the expense of fumigation, pressure from consumers and regulators, and the effects of fumigants on non-target soil organisms such as free-living (non-plant parasitic) nematodes, bacteria, and fungi that play a role in nutrient cycling (Collins et al. 2006; Hamm et al. 2003). Thus, extending the time between fumigation events, reducing the rate of fumigant application, or, eventually finding ways to manipulate soil chemical, physical, and biological properties to provide an effective alternative to fumigation, could be one important avenue to improve soil health in potato systems.

The non-target effects of fumigation on the soil microbial community may contribute to the phenomenon of "fumigation rebound," whereby fumigation treatments provide a short-term benefit, but subsequently disease pressure becomes worse than it was prior to fumigation. This can lead to the "fumigation treadmill," where growers are locked into applying fumigants to maintain crop yield, often with increasing frequency over time (Kinkel 2008).

Soil fumigation with metam sodium has been shown in microcosm studies to significantly reduce soil microbial populations and important soil processes such as carbon and nitrogen mineralization (Ibekwe et al. 2001; Macalady et al. 1998). In a study conducted in Minnesota, Rosen et al. (2018) found that fumigated plots, especially those treated with chloropicrin (which is not commonly used in the PNW) had increased ammonia nitrogen and decreased nitrate nitrogen levels, relative to untreated plots, indicating that fumigation may interfere with nitrification. Collins et al. (2006) conducted a series of studies evaluating fumigation with 1,3-D/metam sodium and white mustard cover cropping on soil bacterial, fungal, and nematode responses on commercial potato fields representing five soil types found in the Columbia Basin. Organisms enumerated by the authors included culturable aerobic bacteria; *Pythium* spp., *Fusarium* spp., and *V. dahliae* fungi; and free living and plant-parasitic nematodes. Fumigation significantly reduced soil recovery of *Pythium* spp. by 97%, *Fusarium* spp. by 84%, and *V. dahliae* by 56% compared to the mustard cover crop treatment. The percentage of bacteria and fungi surviving fumigation was greater for fine- than coarse-textured soils, suggesting physical protection of organisms within the soil matrix, perhaps related to reduced penetration and distribution of the fumigants.

Collins et al. found that populations of the soil fungi measured (*Fusarium* spp., *Pythium* spp. and *V. dahlia*e) and free-living (non-plant parasitic) nematodes were significantly lowered in field plots fumigated with metam sodium/1,3-D compared to cover-cropped field plots. Among all soil series, fumigated treatments had significantly lower fungal populations than the cover crop treatments prior to planting, with the greatest differences found for the Quincy sand, Quincy loamy fine sand, and the Timmerman sandy loam. The numbers of fungi surviving metam sodium/1,3-D fumigation were greater for the fine- than coarse-textured soils, suggesting poor penetration of the fumigant, physical protection of fungal structures by the soil with greater clay and silt content, and biodegradation of bioactive compounds (Warton et al. 2001). Fungi surviving fumigation were 33%, 18%, and 23% lower than the cover crop treatments, respectively, for these three soil series.

Despite the evidence that some soil microbial populations are reduced with fumigation, replacing fumigation with cover crops did not significantly affect carbon or nitrogen mineralization potentials in the Collins et al. study. There was a general trend for mineralized nitrogen from fumigated treatments to be lower than from cover-cropped treatments. Microbial biomass carbon was 8–23% greater in cover crop treatments compared to fumigated treatments. Among the five-soil series, soil fumigation and the incorporation of cover crops had variable effects on soil bacterial populations. There was no pattern of total numbers of culturable aerobic bacteria changing as a function of soil texture, as observed for soil organic carbon and microbial carbon and nitrogen. The numbers of bacteria and fungi surviving fumigation (organismal abundance) were greater for the fine- than coarse-textured soils, suggesting physical protection of organisms within the soil matrix or perhaps a reduced penetration and distribution of the fumigant in fine-textured soils. Reduced fumigant efficacies in soil have been correlated with greater organic carbon and nitrogen contents (Borek et al. 1995).

Smart et al. (2018) characterized bacterial, fungal, oomycete and nematode populations in paired fumigated and non-fumigated potato fields located in Idaho, Oregon, Washington and Minnesota and found that fumigation treatments, in combination with applications of various pesticide and fertilizers, alter soil bacterial diversity. Furthermore, certain treatments, such as chloropicrin, may alter bacterial populations more than other treatments, such as metam sodium.

Technological advances can allow for reduced pesticide use through practices such as site-specific fumigation. King and Taberna (2013) measured fumigant use, yield and tuber quality due to nematode damage on 640 acres of potatoes in eastern Idaho that underwent site-specific fumigation with 1,3-D for control of Columbia root-knot nematode. This practice resulted in a 30% reduction in chemical usage and a production cost savings of approximately $85 per acre. Potato yield and quality (as determined by farm-gate sales) were not adversely affected by site-specific fumigation. The economics of the increased sampling needed for site specific fumigation was not addressed in this paper.

Hansen et al. (2018) compared in-row to broadcast fumigation with metam sodium for control of Verticillium wilt in Rupert, Idaho. The cost of in-row fumigation was estimated at $150 per acre versus $200 per acre for broadcast fumigation. For 'Russet Burbank' potatoes, broadcast fumigation resulted in greater total and marketable yields, and a greater number of US #1 tubers compared to in-row fumigation. These factors resulted in a greater economic return for broadcast versus in-row fumigation. For 'Russet Norkotah', both fumigation methods resulted in similar outcomes in yield and quality.

Besides soil fumigation, other field-applied chemical inputs in potato systems can include herbicides (pre- and post-emergence), non-fumigant nematicides, fungicides (seed, in furrow, and foliar applied), insecticides (seed, in furrow, and foliar applied), and desiccants. The impacts on non-target organisms of each chemical type within these categories is beyond the scope of this review.

Significant overlap exists between cultural IPM approaches and soil health. Many of the cultural practices recommended for IPM in PNW potato production, as described in Hyrnick and Downey (2007), would be expected to improve or enhance soil health. These include: following a 4-year or longer rotation, if possible; planting and incorporating green manure crops; choosing rotation crops that are non-hosts for diseases; and planting winter cover crops for wind and erosion control.

Cover Crops/Green Manures

The term "cover crop" refers to a rotation crop that is not grown as the primary cash crop, but rather to provide some other benefit to the cropping system (e.g., preventing erosion, adding organic matter, or, in the case of legumes, adding nitrogen). A "green manure" is a type of cover crop that is incorporated into the soil before maturity. Cover crops, like other rotation crops, require management, inputs, and planning. A cover crop can be harvested for forage, tilled in, winter killed or terminated using herbicide with residue left on the surface.

<u>Cover crops</u>

Cover crops can scavenge residual nitrate nitrogen in the soil following a shallow rooted crop, like potatoes, preventing it from leaching and making it available for future crops. A cover crop's effectiveness in taking up nitrogen is dependent on its ability to quickly develop an extensive root system in the late fall (Stark and Porter 2005). In a study from the Columbia Basin of Washington, about 29% of nitrogen in a mustard cover crop was cycled into the following potato crop, providing 27-36 lbs of nitrogen per acre for the potatoes (Collins et al. 2007). Well-established winter cover crops (e.g., mustard, rye, wheat), incorporated into the soil in spring can reduce fertilizer nitrogen needs by an estimated 75-150 lbs/acre in irrigated potato production systems of the Columbia Basin (Lang et al. 1999).

In their study of wind erosion in an irrigated potato-sweet corn rotation in the Columbia Basin, Sharatt and Collins (2018) found that delaying the planting of a cover crop (in this case, winter wheat) until the autumn rains arrive may not allow the establishment of a canopy that is effective for controlling wind erosion. They suggested that further research is needed on the influence of the date of cover crop establishment to mitigate against wind erosion in irrigated vegetable production systems.

Leguminous cover crops fix atmospheric nitrogen, making it available for future crops. After plow down of irrigated Austrian peas grown in Aberdeen, Idaho, soil test nitrate levels were at 219 lbs nitrogen per acre and tuber yields increased in the following potato crop by up to 36 cwt per acre (Westermann and Stark 1993).

The specific soil health benefits provided by cover crops in crop rotations depend on the type of cover crop (e.g., small grains, brassicas, legumes), the timing of termination (e.g., prior to maturity, after maturity), and method of termination (e.g., spray out, winter-kill, till in) (Managing Cover Crops Profitably 2012). In the Columbia Basin, winter wheat is generally the cover crop of choice after potatoes because it can provide late season growth, has good winter hardiness, and the seed is inexpensive. Seeding rate is generally increased at a later planting date, with a goal of getting sufficient cover crop biomass to provide protection from wind erosion, but not enough to cause problems for potato planting (McGuire 2011). Winter rye is a noxious weed in wheat crops and should not be used as a cover crop in areas where wheat is produced for seed. Because there is a lack of published information available documenting the benefits of cover crops planted following potatoes in the PNW, more work needs to be done addressing this question.

<u>Green manures</u>

Green manures usually fit well into cropping systems where potatoes follow small grains, green peas, and early sweet corn. In this rotation, green manures are planted after harvest of the previous crop and incorporated into the soil while still green, prior to the potato part of the rotation. A variety of species have been evaluated for use as green manure crops in potato production in the PNW including: broccoli (Ochiai et al. 2008), corn (Davis et al. 1996, 2010), mustard (McGuire 2003, 2012, 2016), oats (Davis et al. 1996, 2010), peas (Davis et al. 1996, 2010; Ochiai et al. 2008), rapeseed (Davis et al. 1996, 2010), rye (Davis et al. 1996, 2010), and sudangrass (Davis et al. 1996, 2004, 2010; Ochiai et al. 2008).

In potato systems, there has been considerable interest in the use of green manures as an alternative to chemical fumigation. In the PNW, much of the literature on green manures is on control of *V. dahliae*, and plant-parasitic nematodes, though Rhizoctonia also may be suppressed with mustard green manure (Johnson et al. 2017). Researchers have observed that when some cover crops are incorporated into the soil with a chisel or disk plow while green, levels of Verticillium wilt on potato are low, even when there are still high levels of *V. dahliae* inoculum in the field (Davis et al. 2010; Ochiai et al. 2008). Two mechanisms, which may operate in conjunction, have been proposed to explain the suppression of Verticillium wilt with green manures: (1) competitive exclusion, and (2) bio-fumigation. Competitive exclusion occurs when the incorporation of green manures leads to increases in the population of some microbes that outcompete *V. dahliae,* and thus effectively inhibit it from infecting the crop (Qin et al. 2008). When suppression is occurring through the mechanism of competitive exclusion rather than bio-fumigation, the amount of green manure may be as important as the plant species in suppressing Verticillium wilt (Ochiai et al. 2008). Thus, it is important to maximize biomass of the green manure crop (McGuire 2016).

In contrast, during bio-fumigation, secondary metabolites of some brassica crops (e.g., mustard, rape) either directly inhibit *V. dahliae* or inhibit the pathogen indirectly by stimulating the growth of antagonistic species (Neubauer et al. 2014). Research on bio-fumigation using green manures is focused on certain species in the family Brassicaceae, primarily oilseed radish (*Raphanus sativus*), oriental mustard (*Brassica juncea*), rapeseed (*Brassica napus*), and white mustard (*Sinapis alba*), that release glucosinolates when tilled into the soil. These compounds then hydrolyze in the soil to release biologically active compounds such as isothiocyanates. Though sorghum-sudangrass or sudangrass has the ability to release hydrogen cyanide during breakdown of the plant compound dhurrin, this mechanism is not believed to be effective against *V. dahliae* (Ochiai et al. 2007).

Biofumigation with Brassica species for control of *V. dahliae*

The general strategy for using Brassica species for bio-fumigation is to choose varieties within a particular species that have high glucosinolate content. Within the plant, glucosinolate concentration generally peaks before flowering and incorporating the green manure before plants produce viable seed is necessary for preventing them from becoming a weed problem. For effective biofumigation, is important for plant material to be sufficiently macerated before incorporation in order to break plant cells and release glucosinolates (Fourie et al. 2016).

In a series of trials by McGuire (2003) near Moses Lake, Washington, ‘Russet Norkotah’ potatoes were planted following multiple mustard green manure crops in a short 2-year wheat-mustard-potato rotation with confirmed presence of damaging levels of *V. dahliae*. Some plots also were treated with metam sodium and others were not. Potato yield did not differ between treatments, suggesting that the mustard green manure can be just as effective as metam sodium in controlling *V. dahliae* in some cases.

Other green manure types for control of *V. dahliae*

Davis (1996) found that sudangrass incorporated into the soil in southeastern Idaho reduced Verticillium wilt and increased yields in potatoes compared to plots receiving no green manure and no fumigation. The increased yields were associated with greater populations of *Fusarium* species that were thought to be biocontrol agents against *Verticillium* (Davis 2004) and also may have been associated with control of plant parasitic nematodes that function in conjunction with *V. dahliae* to cause potato early dying.

In Maine, Larkin et al. (2011) found that a sorghum-sudangrass green manure reduced Verticillium wilt by 18% compared to a barley rotation. However, the sorghum-sudangrass was not as effective as a blend of oriental and white mustards (25% disease reduction), which was less effective than chemical fumigation with metam sodium (35% disease reduction).

Variability of green manure results

Results of research on the use of Brassica species and other green manures in potato systems have been inconsistent, both in the PNW and elsewhere. According to McGuire (2012), differences in results for Brassica green manures are likely due to differences in the length of time using them; differences in green manure crop management that may have impacted the quantity or quality of the incorporated biomass (e.g., nutrient management, timing of incorporation); site variability (e.g., differences in pest levels, soil type) at each location; and differences in potato management. Wheeler and Johnson (2017) reviewed 25 studies on the suppression of *V. dahliae* in potato production using green manures (Figure 5) and noted the following factors that might contribute to the variable results observed in published studies: (1) the species and genotypes of crops planted, (2) cultural factors (e.g., the time the crop is planted), (3) the populations and density of the pathogen(s) present, (4) the presence or absence of aggressive strains, and (5) environmental differences.

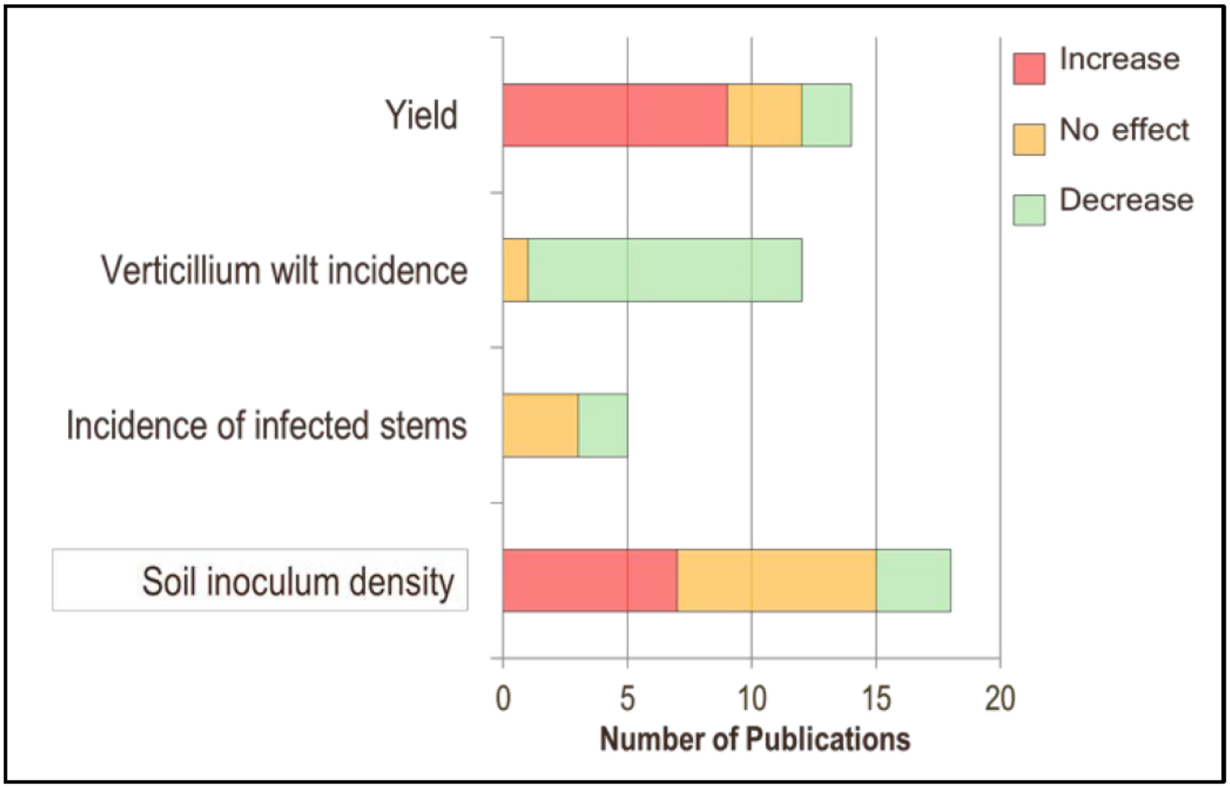

Figure 5. The effects of crop rotation and green manures on potato yield, Verticillium wilt incidence, the incidence of stems infected with *V. dahliae*, and inoculum density as compiled from 25 peer-reviewed publications. (Source: Wheeler and Johnson 2017)

Despite the variability observed, Wheeler and Johnson also observed some reproducible trends in the literature (across cover crop species): (1) suppression of Verticillium wilt can be established in two to three years of green manures (e.g., Davis et al. 1996, 2010), (2) recurrence of wilt can occur when potatoes are grown for two consecutive years (e.g., Davis et al. 2010), and (3) suppression of wilt can be restored after one year of green manures (e.g., Davis et al. 2010).

Though pathogen inoculum levels in soil are used by growers in making decisions about fumigation, pathogen levels in the soil do not always correlate with disease severity or potato yield. In a previously described study, Collins et al. (2006) evaluated the effects of fumigation and white mustard and sudangrass green manures on soil microbial, fungal and nematode responses on commercial potato fields in the Columbia Basin. They found that even though mustard or sudangrass green manure treatments were not able to reduce the pathogen numbers as much as the chemical fumigant, the final yields were not different between the fumigated plots and the ones with mustard or sudangrass green manure crops, suggesting that the level of pathogen inoculum in the soil is not the only factor related to disease incidence and yield.

Furthermore, incorporating plant residue does not always have the effect of reducing *V. dahliae* populations, particularly if they are from a host crop. Incorporation of residue from alfalfa prior to planting potato actually *increased* the level of *V. dahliae* microsclerotia during a 2-year study in the Columbia Basin of Washington (Frederick et al. 2018). The use of green manures for suppressing Verticillium wilt is covered more extensively in a review paper by Al-Hammouri (2011).

<u>Relationship between soil health and Verticillium wilt</u>

In a survey of over 100 commercial potato fields in southeastern Idaho, factors related to soil integrity (i.e., organic matter, organic nitrogen, and increased nutrient availability) were related to wilt suppression and higher tuber yields, whereas factors related to loss of soil integrity (i.e., sodium and reduced nutrient availability) were related to increased wilt and lower tuber yields. *V. dahliae* infections of potato feeder roots and soil organic matter accounted for 36-45% of yield variability during the 3-year study, suggesting that increasing levels of organic matter is one of the factors that could be manipulated for suppression of Verticillium wilt (Davis et al. 2001).

A project funded by the Northwest Potato Research Consortium and led by Markus Kleber at OSU ("Strengthening Soil Health to Suppress Verticillium Wilt in Potato Production Systems," described in Appendix D) was begun in 2017 to elucidate some of the connections between Verticillium wilt, management practices, and soil health. Potato production fields in Idaho, Washington, and Oregon that growers have self-reported as having "high" or "severe" levels of Verticillium wilt are being compared with "healthy" or "low" wilt fields. Growers were surveyed on each field's 5-year management history and soil samples will be analyzed for soil health indicators and for soil microbial community composition and diversity. Soil sampling began in early summer 2018. Results were not yet available at the time this report was written.

Green manures for control of plant-parasitic nematodes

Green manures also have been used to control some of the most important plant-parasitic nematodes that are root pathogens of potatoes (e.g., Columbia root-knot nematode, root-lesion nematode, stubby-root nematode). Alternative management strategies are especially important in light of shortages of Telone II and Vydate, two chemicals commonly used to manage nematodes (Ingham 2017). In a review paper, Oka (2010) describes possible mechanisms involved in green manures' suppression of plant parasitic nematodes including the generation of nematicidal compounds during degradation of the green manure (e.g., glucosinolate-derivative compounds from brassica crops), enhancement of soil microbial population which has antagonistic effects to nematodes, and changes in soil properties that are unfavorable to nematodes. Before selecting a green manure crop for nematode control, it is important to verify the host status of the green manure crop for the target species of nematode. For example, some brassica species are hosts for some important nematodes, such as root-knot nematodes, and may increase the populations rather than reducing them. Efficacy of soil amendments (including green manures) is generally lower than that of chemical control and integration of other control methods likely will be needed to achieve the desired control level (Oka 2010).

The literature on this topic is vast. Abawi and Widmer (2000) provide an overview of the impact of soil health practices on soilborne pathogens, with specific examples from non-potato vegetable production systems in New York State. A recent paper by Fourie et al. (2016) summarizes outcomes of using various brassica species in cropping systems worldwide for suppression of plant-parasitic nematodes. The literature described below is focused on PNW potato systems.

Mojtahedi et al. (1991) evaluated rapeseed (12 varieties of *B. napus* and two varieties of *B. campestris*) green manures for efficacy in suppressing populations of root-knot nematodes in container and microplot experiments near Prosser, Washington. The most effective green manure treatment was *B. napus* L 'Jupiter'. Riga et al. (2011) found that an arugula (*Eruca sativa*) green manure, when used in combination with half the recommended rate of 1,3-D, was able to reduce root knot nematode to below detection limits, while also reducing root-lesion (*P. penetrans*) and stubby-root nematodes (*P. allius*), to below economic thresholds.

Stubby-root nematode, the vector of the *Tobacco rattle virus*, causing corky ringspot disease, is difficult to control with rotation since most plants, including weeds, are hosts to the nematode and the virus. Using green manure crops is thus one of the few available non-fumigant options. Radish cultivars 'Terra Nova' and 'Doublet' have been demonstrated to suppress Columbia root-knot nematode, stubby-root nematode, and corky ringspot (Charlton et al. 2011; O'Neill 2016).

Charlton et al. (2011) examined the ability of green manure crops (arugula, cereal rye, mustard blend, radish, sorghum-sudangrass, and winter wheat) to suppress stubby-root nematodes and corky ringspot disease in potatoes in the Klamath Basin of Oregon. Stubby-root nematode numbers declined under radish ('Doublet' and 'Terranova') and corky ringspot incidence was low to moderate. Yield of US No. 1s ('Modoc') was significantly higher after either type of radish than after winter wheat. Green manure crops of rapeseed and oil radish have led to declines in population densities of root-lesion and Columbia root-knot nematodes (Table 6; Hafez and Palanisamy 2003). Likewise, in a study in Parma, Idaho, Al-Rehiayani et al. (1999) found that populations of Columbia root-knot nematode were reduced after planting oil radish (*Raphanus sativus* L 'Trez') and rapeseed (*B. campestrus* L 'Humus'), with the lowest populations and highest potato yield resulting from the use of oil radish. Plots treated with both oil radish and rapeseed resulted in larger tuber size than plots receiving the chemical control (aldicarb).

Table 6. Influence of green manure crops on nematode populations (numbers indicate nematodes per 500 cc soil sample). (Source: Hafez and Palanisamy 2003)

	Before green manure planting		After green manure incorporation	
Green manure variety	*M. chitwoodii*	*Pratylenchus* spp.	*M. chitwoodii*	*Pratylenchus* spp.
Rapeseed 'Humus'	315	1056	48	280
Oil radish 'Commodore'	190	918	70	181
Oil radish 'Colonel'	152	735	5	130
Fallow	113	495	40	311

In Colorado, O’Neill (2016) found that the most promising cultivars of brassica species for increasing soil tilth and suppressing Columbia root-knot nematode were radishes ‘Anaconda’, ‘Biofum Summer’, ‘Cassius’, ‘Doublet’, ‘Graza’, and ‘Terranova’, ; Ethiopian cabbage ‘Corrine’; and Turnip x Kale hybrid ‘Winfred’. Cyst and potato rot nematodes are not suppressed by green manures (Hirnyck and Downey 2007).

Green manures for control of other soilborne fungal pathogens

Several studies have examined the use of green manure for control of other soilborne fungal pathogens. A white mustard green manure (‘Martigena’) grown the previous fall suppressed Rhizoctonia canker in potato. Rhizoctonia incidence, severity, and conditional severity were not significantly different for plots with the white mustard green manure than plots treated with both white mustard green manure and a fungicide during a 2010-2011 study in Pasco, Washington (Johnson et al. 2017). In the same study, plots where a sudangrass green manure was grown had significantly greater conditional severity of Rhizoctonia canker than plots planted with a mustard green manure. In Maine, Larkin et al. (2011) found that a blend of white mustard and oriental mustard suppressed both scab and Rhizoctonia on potato better than a sorghum-sudangrass green manure or a barley rotation.

Black dot management includes management of Verticillium wilt and other causes of early dying in potatoes, since co-infection will increase damage (Johnson and Cummings 2015). Extended rotations have been demonstrated to reduce the incidence of black dot (Johnson and Cummings 2015), though no literature was found specifically on the effects of green manures on black dot.

Other benefits of green manures

Other soil building properties of green manures may be as important as disease suppression. A 2010 survey of Washington potato growers using green manures found that the soil building of the green manures was important to more growers than disease suppression (McGuire 2012).

Benefits of green manures have been found to extend beyond suppression of Verticillium wilt. Davis et al. (2004) attributed yield increases beyond what would have been expected from suppressive effects alone to increases in mineralizable soil nitrogen. The addition of organic matter from green manures can be especially important in coarse textured soils and can lead to benefits such as improved water infiltration rates. In a study of paired fields near Moses Lake, Washington, McGuire (2003) found that infiltration rates for soils receiving mustard green manures were from 2 to 10 times greater than comparable fields not receiving green manures.

To protect fields from spring erosion during establishment of the potato crop, growers can grow a green manure crop immediately following the harvest of the crop before potatoes and incorporate it into the soil in the fall. This provides some amount of protection from wind erosion in the spring. Cover crops can be managed in ways to reduce early season erosion – timing the cover crop termination and managing the residue are especially important for erosion control (McGuire 2011). However, in a case where erosion potential was severe, Sharratt et al. (2018) found that two years of green manure alone was not enough to influence early-season wind erosion or soil erodible characteristics the spring after incorporation, suggesting that more years of green manure or reduced tillage may be necessary in these cases.

Economics of green manure

University of Idaho researchers conducted an economic evaluation on a full season green manure legume in a potato rotation in southeastern Idaho. For this evaluation, a 3-year rotation of grain/Austrian pea/potato was compared to a 3-year rotation of grain/grain/potato. Potato yields in the study following Austrian winter pea were about 50 cwt per acre higher than average for the grain/grain/potato rotations in the area, while grain yields were about average. Potato quality was above average and disease problems were reduced. Net return was essentially identical between the rotations, with the rotation including Austrian pea resulting in substantially lower fertilizer and pesticide use (Finnigan et al. 2003).

A comparison of costs and returns in potato production systems with and without green manures by Finnegan et al. (2003) is shown in Table 7. In this system, $130/acre was saved by not fumigating. This savings, along with an additional $180/acre due to increased yield, more than compensated for the cost of the green manure ($77.37/acre).

Table 7. Costs and returns in a potato production system with and without green manures. Adapted from University of Idaho enterprise budget EBB4-PoI-99. Southeastern Idaho Russet Burbank No Storage. (Source: Finnegan et al. 2003)

	Conventional system (cost/acre)	Green manure system (cost/acre)
Gross returns	$1,485 (330 cwt @ $4.50)	$1.665 (370 cwt @ $4.50)
Irrigation	$55.52	$55.52
Custom	$57.05	$57.05
Fertilizer	$147.00	$79.00 (no micros or late P)
Green manure costs	0	$77.37
Other costs	$69	$69
Potato seed costs	$151	$151
Pesticide costs	$292	$162 (no fumigation)
Labor, fuel, repair, interest	$207	$207
Total operating costs/acre	$979	$858
Net returns	**$506**	**$807**

The cost of soil fumigation has increased since 2003. Soil fumigation costs in the PNW (as determined from recent crop enterprise budgets) varied from $259 per acre for 'Russet Burbank' fumigated with metam sodium in southcentral Idaho (Eborn 2017) to $400 per acre for 'Russet Norkotah' receiving a double ground application of metam sodium in Washington (Galinato and Tozer 2015). Ingham et al. (1999) estimated the cost of non-fumigant nematicides at $120-$220 per acre ($176-$322 in 2016 dollars). When used in certain cropping systems, green manures can replace expensive fumigants or bring nematode populations down to a level where less expensive non-fumigant chemical control might be effective. However, the degree and benefit of this practice depends on many factors, varying between systems and between fields. Cover crops, including green manures, require management, fertilizer, irrigation, and labor. Some of the costs of fertilizing green manures will be recouped the following year as residues from the green manures break down in soil and become available to the potato crop. On-farm testing is recommended for determining the appropriate varieties for a site and anticipating yield impacts on the potato crop that follows (McGuire 2016). McGuire (2003) estimated that growers could save an estimated $66 per acre by use of mustard green manures instead of metam sodium. Riga (2011) found that an arugula green manure, used in combination with half the recommended rate of 1,3-D cost about 35% less than the full rate of fumigant.

Washington State University Extension has done extensive work to make growers aware of the practice of mustard green manure through field days, presentations, and publications (McGuire 2011, 2016; McGuire et al. 2017; Yorgey et al. 2017). Sales of mustard seed in the Columbia Basin of Washington and Oregon indicates that acreage planted to mustard has increased from 1,800 acres in 1999 to about 30,000 in 2012. In 2017, acreage in mustard was estimated at 25,000 (McGuire, n.d.). Most mustard is being grown before potatoes, but this number also includes mustard acreage grown before peas and onions. A recently published case study and accompanying video highlight Dale Gies, a grower near Moses Lake, Washington, who uses a mustard/arugula cover crop mix before potatoes, which eliminates the need for fumigation despite his intensive 2-year potato rotation (Yorgey et al. 2017).

There has been some limited adoption of green manures (mustard, oilseed radish) in potato rotations in eastern Idaho, possibly due to the lack of options for other rotation crops. Green manures are less commonly used in other parts of Idaho. Barriers to adoption include not wanting to have another crop to manage, restrictions on water use, resistance to change, shorter growing season, and a learning curve to estimating nitrogen release from an incorporated cover crop. It has been reported that in the Magic Valley of Idaho, a number of growers tried green manure in the late 2000s, but these growers gave up after becoming frustrated that the green manure tied up nitrogen in the potato crop (J. Miller, personal communication). The wide variety of soil and climate conditions among the diversity of potato production systems will require refinement for the use of green manures in each system and economic analysis applicable to each system. For example, although field demonstrations and research on use of green manures often show a benefit to the following potato crop for either yield or quality, the increases may not always cover the cost of producing the green manure. Green manure may not always result in a noticeable increase in potato yield or quality, particularly for fields with high levels of organic matter or biological activity, or without a history of potato disease problems (Finnigan et al. 2003).

Animal Manures, Composts, and Alternative Fertilizers

In addition to providing nutrients, organic amendments such as animal manures and composts add organic matter to soils, thus feeding the soil microbial population and presumably improving soil health. These amendments import nutrients into the system and therefore can reduce chemical fertilizer costs. Because transportation and handling of compost and manure is costly, their practical use is limited to areas in relatively close proximity to where they are produced and they are often more expensive to use than field grown plant inputs (e.g., cover crops, crop residues, green manure). Organic amendments also need to be carefully selected to avoid the introduction of weed seeds and unwanted contaminants (e.g., heavy metals, plastics).

Nutrient availability from organic nutrient sources, such as manure and compost, is highly dependent on a number of factors (e.g., amendment composition, soil moisture, soil microbial community, temperature) and it is important to time crop nutrient demands with nutrient availability. A number of studies have examined nutrient availability and uptake in PNW potato systems and associated yield benefits from manure (Moore et al. 2016b, 2016c); compost (Collins et al. 2016b; Moore et al. 2011); alternative fertilizers such as phosphorus solids recovered from anaerobic digestion (Collins et al. 2016a); biochar enriched with anaerobic digested dairy manure effluent (Collins et al. 2013); humic acid products (Seyedbagheri 2010); and, fertilizers for use in certified organic production, such as seed meals, mint compost, and commercially available organic fertilizers (Collins et al. 2016b).

Animal Manures

Manure is quite variable and its composition is a function of species, diet, storage, water and bedding content. In some areas of the PNW, where potato production and dairies are in close proximity to each other, use of manure in rotations involving potatoes is becoming common. Manure application occurs in a non-potato year of the rotation. In some areas of Idaho, copper toxicity has impacted potatoes due to the copper in dairy manure accumulating from animal foot baths (B. Buhrig, personal communication), an example of a new issue that potato growers are navigating as overlap increases between dairies and potato production.

Recent work by Moore et al. (2016b) found that yields of ‘Russet Burbank’ potato near Kimberly, Idaho were lower after two years of annual application of 48 tons/acre of dairy manure (tuber yield = 447 cwt/acre) compared to biennial applications of 48 tons/acre (one application over two years; tuber yield = 523 cwt/acre) and annual applications of 16 tons/acre (tuber yield = 519 cwt/acre), which were possibly due to a salinity problem. Manure applications significantly increased the <4 ounce, 4-6 ounce, and >12 ounce tuber size class yields, with increases in the >12 ounce class attributed to improved soil structure and increases in the <4 ounce and 4-6 ounce classes attributed to late season nitrogen availability. Moore et al. found that cumulative dairy manure applications from 64 to 196 tons/acre increased soil organic matter at a 12 inch soil depth from 1.5% (fertilizer-only treatment) to 2.0-3.1%, and caused a significant decrease in soil bulk density and an increase in soil porosity. Manure treatments resulted in greater incidence of tuber sugar ends, a quality issue, when compared to the fertilizer treatment. Manure applications were also found to have no significant effect on wireworm or zebra chip occurrence, presence of pathogenic *E. coli* (none was detected), or weed populations (Moore et al. 2016b).

In a study where manure was applied to a potato rotation preceding small grains in Kimberly, Idaho, Moore et al. (2016c) found that soil organic matter increased 0.02% for every ton of manure-derived organic matter applied. Manure application can lead to soil salinity issues and decrease aggregate stability in low rainfall areas. Scores calculated using the Haney Soil Health Index indicated that soils receiving manure were healthier (5.4-8.4) compared to the control (4.1) and the fertilizer treatment (4.7), with greater manure application generally resulting in a greater Haney Soil Health score. However, the authors caution that the scores from the Haney Soil Health Index are misleading since they don't take the electrical conductivity or sodium adsorption ratio into account (Moore et al. 2016c).

One factor limiting the use of manures in potato production is that some potato growers avoid applying manure because of concern that it will increase incidence of common scab, though this is more of a problem with fresh pack potatoes than with processing potatoes. While in general, soils rich in non-decomposed organic matter favor common scab (Hirnyck and Downey 2007), the research on this topic has had mixed results with some studies showing incidence of scab after manure application being reduced (Ninh et al. 2015, study conducted in Michigan), unchanged (Moore et al. 2011, study conducted in Idaho), or increased after compost application (Larkin and Tavantzis 2013, study conducted in Maine). Moore et al. (2011) compared fresh and composted dairy manure solids with conventional fertilizer in Idaho and found that yield increased as a result of fresh and composted manure application with no effect on tuber diseases, disorders, quality, or *E. coli* populations.

In some circumstances manure has had disease suppressive effects. For example, Conn and Lazorovits (1999) found that the volatile fatty acids in liquid swine manure suppressed both Verticillium wilt and common scab in acidic (pH<5.5) soils in Ontario. Lazorovits (2010) tested organic amendments high in nitrogen (e.g., soymeal, poultry manure) or high in volatile fatty acids (e.g., liquid swine manure, fish emulsion) for their ability to suppress soilborne diseases in potato systems in Ontario and Prince Edward Island, but when suppression occurred, it often was site and amendment specific. While the use of organic amendments for site-specific control may be possible in the future, at present, economic constraints with accessing large amounts of uniform organic amendments prevent it from being a viable approach for most potato growers.

Use of manure in potato systems can have benefits or potential consequences depending on the type of manure, its storage, and the timing of application. In order to minimize any potential food safety risks, manure is usually applied to cover crops or forage crops grown in rotation with potatoes. A WSU case study profiles a grower from the northern Columbia Basin who, in addition to high residue farming and strip tillage during the rotation, incorporates 10 to 15 tons of manure per acre during the tillage operations prior to leasing the ground for potato production, or surface applies the same amount on the crop preceding potatoes in the rotation (Yorgey et al. 2018). It is important to follow specifications for manure application for Good Agricultural Practices (GAP). The GAP program requires 120 days between application of manure and harvest of potatoes, which would allow for applications of manure up until early spring for most potato crops (Moore and Satterwhite 2015). Organic amendments such as compost or manure usually require some amount of decomposition to occur to release nitrogen, providing another reason to apply them to a crop preceding the high value potato crop.

Other potential issues with using manure as a fertility source in potatoes include economic risk related to inconsistent nutrient availability, the environmental risk from excessive P application associated with repeated manure applications, and build-up of salinity or copper in soils. Some recommendations for potato growers applying manure are outlined in Moore and Satterwhite's (2015) article in Potato Progress.

Compost

The composition of compost can vary depending on feedstocks, but it is usually lower in nutrient content than manure. Since the organic matter in compost has already undergone decomposition, the carbon input from compost is generally more stable when amended to soil than manure. Additionally, applying mature compost poses a lower risk than applying manure from a food safety perspective.

There are several studies from other parts of the country looking at the effect of composts on potato rotations. In Connecticut, LaMondia et al. (1987) observed an increased marketable yield of potatoes after the addition of spent mushroom compost, presumably due to suppression of Verticillium wilt. Larkin et al. (2017) examined a number of practices for improving soil health in an 8-year study of different potato cropping systems in Maine including mustard green manure and addition of compost. The treatment which had the greatest effects on soil health involved yearly compost amendments, and a 3-year rotation of potatoes (barley/timothy–timothy–potato) with reduced tillage. The addition of compost increased potato yields but did not reduce incidence of black scurf or common scab.

Research on organic (carbon-based) amendments in potatoes in the PNW has focused primarily on nutrient availability, rather than specific effects on soil health. However, there is a substantial body of knowledge that is not specific to potatoes, related to the effects of organic amendments on soil health in the Columbia Basin that could be relevant.

McGuire et al. (2017) compared paired fields in an evaluation of three soil improvement practices (cover cropping, high residue farming, organic amendments) used in irrigated soils in the Columbia Basin across a variety of crops (including potatoes). The authors found that while the use of green manure improved soil organic matter, soil protein, and infiltration (2^{nd} inch of water), organic amendments (4-5 tons/acre of screened chicken or cow manure or waste from mint oil processing) improved soil organic matter, soil protein, and soil respiration. The greatest number of measures (soil organic matter, active carbon, soil protein, soil respiration, and available water capacity) were improved by integrating all three practices (Table 8). Though the sample size was small, the idea that multiple practices tend to have complementary effects is supported by Bernard et al. (2012) who conducted a study in Maine looking at the effects of compost application, rapeseed green manure, and application of biocontrol products in potato systems. In this study, each treatment had specific and significant effects on the soil microbial population.

Table 8. Soil health measurements with and without soil improvement practices. The high residue farming practice is not included because there were only two paired fields to compare. (Modified from McGuire et al. 2017)

		Measured Soil Quality Characteristics							
		Soil organic matter (%)	Active carbon (ppm)	Soil protein (mg/g)	Soil respiration (mg/g)	Available water capacity (mg/g)	Infiltration 1st inch (minutes)	Infiltration 2nd inch (minutes)	Bulk density (g/cm^3)
All practices combined	With	2.0	461	5.3	0.5	0.182	12.5	16.5	1.34
	Without	1.8	374	4.0	0.4	0.165	14.9	22.0	1.34
	Effects	☺	☺	☺	☺	☺	😐	😐	😐
Organic amendments	With	2.6	566	6.4	0.6	0.184	27.0	27.2	1.39
	Without	2.2	480	4.6	0.4	0.184	17.0	18.2	1.41
	Effects	☺	😐	☺	☺	😐	😐	😐	😐
Green manures	With	1.9	364	4.6	0.4	0.185	3.0	7.9	1.23
	Without	1.5	329	3.6	0.3	0.168	19.6	16.3	1.27
	Effects	☺	😐	☺	😐	😐	😐	☺	😐

Effects on soil

☺	Positive effect (P > 0.05 probability level)
😐	No effect

Microbial Inoculants

Microbial inoculants have been used in some settings to add beneficial organisms to the soil. Some research has been done in Maine looking at biocontrol organisms (e.g., *Bacillus subtilis* GB03, *Rhizoctonia solani* hypovirulent isolate Rhs1A1, and *Trichoderma virens*) both in terms of controlling soilborne disease such as Rhizoctonia stem and stolon canker and black scurf, and common scab (Larkin and Tavantis 2013), and the effects on the soil microbial community (Bernard et al. 2012). Al-Reyhaiyani et al. (1999) in a greenhouse study conducted in Parma, Idaho, reduced the population of Columbia root-knot nematode by using isolates of the bacteria *Bacillus megaterium*, alone and in combination with green manure. Currently, use of biocontrol organisms is uncommon on a commercial scale in PNW potato systems. These products, which can be expensive, may be difficult to justify without a baseline understanding of microbial processes in the soil (Lehman et al. 2015a) along with compelling research supporting their effects on yields in the region. Many microbial inoculants lack the consistency and efficacy that growers require for controlling diseases (Kinkel 2008).

Impact of Potato Breeding and Potato Seed Production on Soilborne Disease

Soilborne disease is directly related to soil health. In an effort to limit disease impacts to crop production, complementary efforts by plant breeders and plant pathologists are important. However, despite over a century of resistance breeding, heavy inputs of pesticides still are needed for potatoes to realize their genetic yield potential. Jansky (2000) pointed to the following reasons: the polyploid nature of the crop, the need to incorporate other quality traits, a lack of understanding of inheritance of resistance, inadequate resistance screening methods for large populations, and insufficient knowledge of the effects of interactions among resistance mechanisms. Breeders also have found it difficult to penetrate potato grower markets with new varieties and the acreages planted to the main commercial varieties have remained static for a number of years (Clarke 2014). The market, driven by the quick service restaurant (QSR) industry, has a conservative approach to accepting a new cultivar as well. For example, though the cultivar ‘Clearwater Russet’ was released in 2009, its recent acceptance by McDonald’s has caused a shortage in seed supply (R. Knowles, personal communication). Though several new varieties have been introduced through the Tri-State Variety Development Program, ‘Russet Burbank’ still represents a significant percentage of potato production in the PNW (Figure 6).

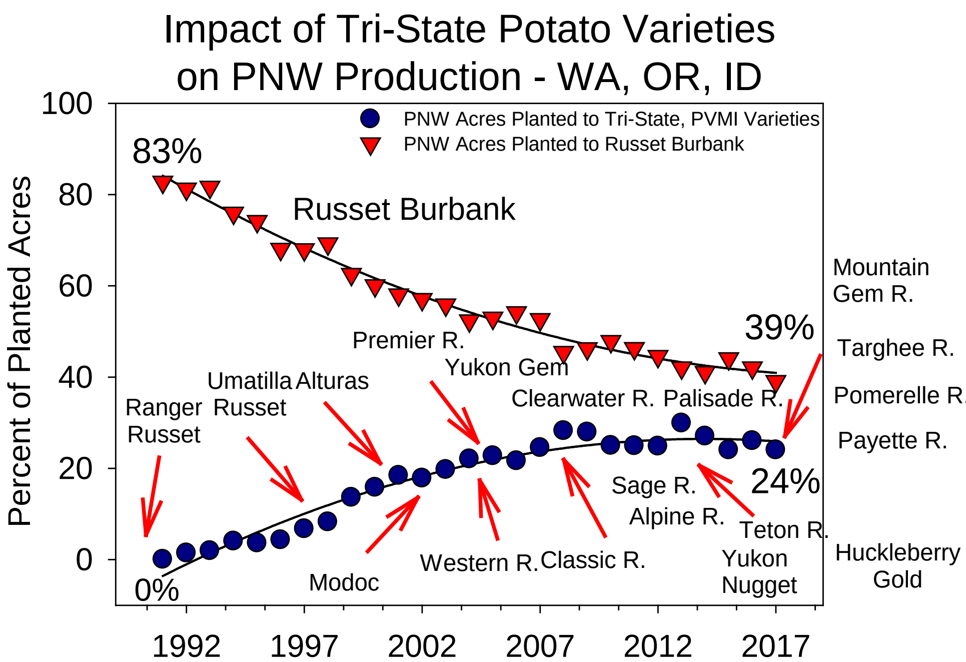

Figure 6. Impact of Tri-State and Potato Variety Management Institute (PVMI) potato varieties on PNW production. (Source: Pavek and Knowles, 2018; Compiled from USDA NASS data)

Despite these challenges, breeding represents an important strategy for reducing pesticide use in potatoes through genetic resistance and possibly affects soil health in other ways (e.g., nutrient use efficiency). The development and adoption of cultivars resistant to specific pathogens would also reduce inoculum levels of these pathogens in soil where these cultivars are grown. Additionally, extremely high levels of soil inoculum can be avoided when ultra-susceptible cultivars are not grown (Johnson and Dung 2010). Though it is beyond the scope of this review, the potential to use GxExM (genetics x environment x management) to impact soil health exists, with potato breeding efforts being a key element. Examples of pathogen and pest resistance screening by breeding programs in the region include: Verticillium wilt, common scab, Columbia root-knot nematode, and potato cyst nematode species (*Globodera rostochiensis*, *G. pallida*, *G. ellingtonae*). Breeding programs also are starting to screen for host resistance to *Potato mop-top* virus. (J. Whitworth, personal communication).

Though beyond the scope of this report, efforts to ensure disease-free seed tubers are also of critical importance in any effort to limit disease, since many potato pathogens can be seedborne as well as soilborne. Possible approaches for accomplishing this goal include: more work on the use of hydroponic systems, true potato seed, or advanced diagnostics in seed potato production (D. Inglis, personal communication).

Recommendations for Future Research on Improving Soil Health in Potato Cropping Systems in the PNW

The literature on soil health in potato cropping systems in the PNW is largely related to the management of soilborne pathogens by crop rotation and cover cropping. Though soil health discussed in the context of potato systems is sometimes conflated with low soilborne pathogen pressure, it is important to note that pathogen pressure is only one aspect of soil health, albeit an important one. In some discussions of soil health, an assumption is made that soils having the attributes associated with soil health will not have problems with soilborne pathogens. However, this assumption oversimplifies the relationship between soil health and soilborne pathogens. For this reason, it is helpful to think of practices to improve soil health as just some of the many management strategies available for improving crop yield and quality.

Much of the work on identifying useful indicators of soil health (e.g., respiration, active carbon) has occurred in areas of the U.S. with climates and soils that are very different from the major potato production areas in the PNW. Research is needed to better understand the relationships between these indicators and potato yield and quality and soilborne pathogens. This work would allow fine tuning the use of soil health indicators to better guide management decisions in these systems.

Though the literature underscores a general understanding of soil management practices, the specific circumstances under which implementing these practices in potato production imparts better yield and quality, and economic gain, often is unclear. There are still significant gaps in understanding the specific effects of practices, such as lengthening and diversifying crop rotations (including the use of cover crops and green manures), applying organic amendments, and reducing tillage on soil health in general, on specific soil issues (e.g., erosion, water infiltration, suppression of soilborne pathogens), on yield and quality of potatoes, and on net returns across diverse PNW potato production systems.

Researching soil health in PNW potato production necessitates a systems level approach to address the erosion, fertility, and organic matter issues unique to each system as well as the soilborne pathogens of primary concern. The literature to date makes clear that rotation diversity and rotation length are critical drivers of soil health – but soil health considerations do not generally drive decisions about diversity or length of rotations. Rotation diversity is influenced by the markets in place for rotation crops and their fit within specific potato production system practices and sometimes may be driven by crop choices made by other growers. Rotation length is largely a function of economics and potato processor needs. While many of the “easy fixes” for improving yield (e.g., optimizing soil fertility, use of soil fumigants and other chemical controls) have already been established, what remains now are the more difficult challenges that will require approaches that fit within the specific constraints of each PNW potato cropping system. Rather than taking a “one size fits all” approach, it will be necessary to target research projects towards practices that hold the most promise for specific cropping systems and locations. For example, a practice for improving soil health that makes sense in the Klamath Basin of Oregon may have little relevance in the Magic Valley of Idaho. Likewise, barriers to adopting these practices and effective strategies for overcoming these barriers are likely to vary between production systems.

While the specific research priorities that hold the most promise for particular PNW potato production systems will be best identified by the researchers working within those systems, this review is meant to provide an overall framework to guide future funding in this area, rather than to identify specific research gaps. Based on the findings from this literature review, future research funding should be directed to projects with the following goals:

1) **Elucidate the relationship between practices that improve soil health and soil health indicators, soilborne pathogens, and potato yield and quality in PNW potato systems.** These practices fall into three general categories: practices to stop soil degradation (e.g., eliminating erosion, reducing tillage), practices to improve soil-water relations and management (e.g., reducing tillage, increasing organic matter through cover cropping, and use of organic amendments), and practices that can reduce or eliminate fumigation (e.g., cover cropping). Further research may reveal additional practices for improving soil health that should be considered, beyond those discussed in this report. The information gathered as part of Goal 1 should inform the work described in Goal 2.

2) **Develop a soil health assessment or calibrate an existing assessment for use in PNW potato systems and establish a baseline understanding of soil health in PNW potato systems.** The information gathered in Goal 1 should inform the development or calibration of a soil health assessment for use in PNW potato cropping systems. The assessment method should: (a) include indicators that are sensitive to changes in practices (e.g., rotation length, rotation diversity, inclusion of cover crops/green manures, reduced tillage); (b) take into account soilborne pathogen pressure (e.g., soil inoculum levels) and resulting crop damage

and economic impact from these pathogens; and (c) be predictive of plant health, crop yield, and crop quality. Research also is needed to aid interpretation of soil health indicators, directing growers toward specific management decisions that will lead to improved crop performance.

3) **Gather additional information to characterize distinct potato cropping systems in the PNW and identify specific soil health challenges and opportunities unique to each system.** Though this document begins this process, much of the information on cropping system practices falls outside of published literature and, thus, was not possible to fully explore.

4) **Develop a better understanding of the barriers that currently prevent adoption of practices known to improve soil health and address these barriers. Quantify the economic and other tradeoffs that exist for particular practices or suites of practices, in order to provide PNW potato growers with important decision-making tools for optimizing tradeoffs**. Examples of barriers to adoption include the economic uncertainty of implementing new practices, the lack of understanding of how new practices might affect soilborne pathogens and crop nutrient needs, constraints coming from the supply chain, limited available markets for additional rotational crops, and the difficulty of implementing changes on leased land. In order to address the barrier of economic uncertainty, for each practice, or suite of practices, the tradeoffs that exist (e.g., length of potato rotation vs. yield and quality, soil health benefits vs. the cost of the practices needed to obtain them) should be quantified to provide growers in PNW potato production systems with decision-making tools for optimizing these tradeoffs.

5) **Establish long-term research and demonstration sites in the various potato cropping systems in the PNW to provide information on both economic and agronomic changes resulting from these approaches.** Long-term research conducted in different PNW potato cropping systems is needed to test the effects of changes in practices on soil health, disease pressure, potato yield and quality, and net returns. Long-term potato cropping system research would provide valuable information including economic comparisons of system changes to improve soil health (such as that undertaken by Khakbazan et al. [2016] in Alberta potato systems), including input costs, and returns over the whole rotation. This type of research can also be used to understand which practices will improve soil health, but do not provide economic benefits for growers in the current production systems.

In the pursuit of Goals 1, 4, and 5, above, considering two tiers of possible changes that can be made to improve potato production through soil health may be helpful: incremental change and whole system change. Incremental change involves a change to one part of the cropping system. This type of change is relatively low risk to growers, and results are usually (though not always) apparent in a growing season. Some examples of incremental change include use of a green manure cover crop, variable rate fumigation, and the addition of organic amendments. Short-term research investment should be made to identify promising opportunities to implement incremental changes to the PNW potato production systems described in this review that improve soil health without making major shifts in cropping systems.

However, because there are limitations on improving the biological components of soil health while soil fumigation is being used, whole system changes should be considered as well. Whole-system changes are large, and could include, for example, incorporating multiple approaches with the goal of manipulating the soil chemical, physical, and biological environment enough to eliminate the need for fumigation. As discussed in this review, implementing multiple practices often is more effective in improving soil health than a single practice. Any set of changes that manipulates the soil chemical, physical and biological environment enough to eliminate the need for fumigation, would likely involve a combination of practices such as extending rotation length, exploring different rotation crops or management of rotation crops, incorporating organic amendments, adding cover crops or green manure crops to rotations, and reducing tillage.

Research methods may also need to be adapted. As noted by Hopkins et al. (2007) there often is a reluctance by PNW potato growers to adopt best management practices (BMP) due to concerns about the applicability of plot-scale research to larger scale farm operations, confusion resulting from different researchers giving conflicting recommendations, and a hesitancy to change practices when what they have been doing to date is working. Hopkins et al. (2007) found that the two factors that most influenced adoption of BMPs were that the project was conducted at field scale in cooperation with model growers and that multiple practices were integrated into one management style (systems approach). Strategies for improving soil health are likely to be even more complex than the BMPs examined by Hopkins et al., so effective approaches need to be developed to encourage grower adoption. Innovative strategies for lessening the economic risk to growers may be one way to encourage adoption of practices to improve soil health.

Finally, because soil health is an active area of research in the PNW and nationwide, it will be important to identify PNW potato research that can dovetail with ongoing soil health projects (some of which are included in Appendix D), or other projects funded in the future. In places where potatoes are grown in rotation with other annual crops (e.g., vegetable crops), there may also be opportunities for collaboration on soil health projects with relevance to other commodity groups.

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Appendices

Appendix A: Report from Noble Research Foundation meeting on soil health in potato production

ENHANCING SOIL HEALTH

IN POTATO PRODUCTION SYSTEMS:

A Workshop Report

Jointly convened by the National Potato Council, Samuel Roberts Noble Foundation (now the Noble Research Institute), and the Soil Health Institute

March 27-29, 2017

Ardmore, OK

INTRODUCTION

The concept of soil health has garnered the attention of farmers, ranchers, scientists, agricultural industry, environmental organizations, and others at a global scale. Soil health is defined as the capacity of a soil to function as a vital living ecosystem that supports plants, animals, and humans. While practices have been identified that sustain and enhance soil functions, such as providing water and nutrients, some practices traditionally employed in potato production present significant challenges for improving soil health. Research has shown, however, that when practices to enhance soil health are implemented, potato yield can be increased and disease incidence reduced.

A significant opportunity exists to develop the science-based knowledge needed for farmers to enhance soil health in potato systems. To lay the groundwork for realizing that opportunity, the National Potato Council requested assistance from leaders of the Samuel Roberts Noble Foundation (now the Noble Research Institute) and the Soil Health Institute. The decision was subsequently made to hold a workshop sponsored by the Samuel Roberts Noble Foundation to engage farmers, scientists, field practitioners, and potato industry representatives in identifying critical needs to be addressed.

A strategic agenda was jointly developed and facilitated by the Samuel Roberts Noble Foundation in which the scientific basis for soil health was presented by the Soil Health Institute, management practices commonly used in potato production were described by a panel of successful potato producers, principles of soil health management were presented by USDA-NRCS, and opportunities and barriers to adopting those principles in the context of potato production were identified by all participants. This resulted in a list of next steps for further consideration, refinement, and pursuit. The following is a summary of key discussions and deliberations.

MANAGEMENT PRACTICES USED IN POTATO PRODUCTION

In general, potato production involves several soil-disturbing practices, including both primary and secondary tillage, weed cultivation, hilling, and harvesting. In fact, the harvesting practice is particularly disruptive, where the "hill" of potatoes is passed over a chain to separate soil, rocks, and potato vines from the tubers. Such practices physically disrupt soil aggregates and promote loss of soil organic C (i.e., soil organic matter). Additional practices such as fumigation and pesticide application may be expected to at least temporarily impact soil microbial activity and diversity. Scientists in attendance felt that reliance on fumigation creates reliance on more fumigation, and that it can take years to restore the soil microbial communities. Others noted the market drivers influencing a producer's decision to fumigate.

Potato producers at the meeting discussed a range of rotations used in their potato cropping systems. In Washington state, sweet corn-wheat-bluegrass sod-potato was discussed. This rotation also sometimes included onion. In Colorado, the rotation was generally less diverse, often characterized by barley-potato, but it was also recognized that a summer green manure was becoming more popular. In Maine, two-year rotations are generally used, with potato rotated with either oats or barley on approximately one-half of the potato acres. A relatively common three-year rotation in Maine is oats-clover-potato. Two-year rotations are also common in Idaho (wheat or barley followed by potato) and in Michigan (potato-wheat with winter cover crop), but with some growers in Michigan using a three-year rotation of alfalfa-alfalfa-potato. Participants generally described a growing emphasis on cover crops across all production regions, as exemplified by the system described for Minnesota as potato/winter rye cover-corn-spring grain/winter rye cover-potato/winter rye cover. One producer noted that processors in the US often write three-year rotations into a contract as compared to a five-to seven-year, mandated rotation in Europe due to pests and lack of chemical control options.

Participants discussed microbial amendments to control nematodes where root length and plant height are analyzed as a measure of success. Some producers are resistant to microbial amendments ("bugs in a jug") and are skeptical of replacing an existing soil microbial community with an alternate, introduced microbial community. Instead of using microbial amendments to enhance diversity and control nematodes, some producers focus on feeding the soil using poultry or cow manure to stimulate and increase biodiversity. Many acknowledged challenges in controlling powdery scab and verticillium wilt.

Producers considered economics as perhaps the most significant factor influencing implementation of soil health-promoting practices. The production costs of a long-season storage potato can amount to almost $5,000 per acre. Declining returns on investment; the itinerant nature of cash-renting ground for potato production; huge capital investment; and industry demands for the "perfect potato" with high gravity, no internal defects, and no foreign material all present barriers to adopting soil health management systems. Additional water-related issues such as increasing cost of water in Colorado, a depleting aquifer in Idaho, and "super-storms" that result in soil erosion in Maine are also limiting factors.

The group identified the lack of a baseline understanding of soil health and standardized soil health measurement as limiting factors to adoption. Few producers understand how to interpret various soil tests, including the Haney Test, Cornell's Comprehensive Assessment for Soil Health (CASH), Soil Management Assessment Framework (SMAF), soil phospholipid fatty acid analysis (PLFA), and others. Producers want to better understand the impact of tillage, no-tillage, cover crops, and various crop rotations on soil health.

PRINCIPLES OF SOIL HEALTH

USDA-NRCS Soil Health Specialist, Marlon Winger, described his experiences teaching soil health workshops to farmers in Wyoming, Montana and Idaho. In recent years, he has observed that farmers are tired of losing standing water to evaporation, and are beginning to see soil health as a means to increase resilience to a changing climate; specifically, farmers are implementing soil health-promoting practices to take the 'evaporation' out of 'evapotranspiration' ('E out of ET').

NRCS promotes five core soil health principles for all cropping systems:

a. <u>Minimize disturbance</u>
b. <u>Keep the soil covered</u>
c. <u>Increase crop diversity</u>
d. <u>Keep a living root (i.e. cover crops)</u>
e. <u>Integrate livestock</u>

To date, Winger has not met a producer who has implemented these principles and has reverted back to previous management practices. He noted that one producer in North Dakota has tried 87 different cover crops and has not found one he does not like. A producer in Idaho has implemented these practices and has not fumigated for nematodes in six years. Marlon teaches 40 workshops per year and sees that farmers are starved for soil health information, as evidenced by the fact that they often attend multiple sessions in the same year.

NRCS defines soil health as *the capacity for a soil to function as a vibrant, living ecosystem, that sustains plants, animals and humans*. These functions of healthy soil include nutrient cycling, storing plant available water, chemical decomposition and pest suppression. He considers that each function is strengthened or weakened depending, in large part, on the amount of carbon in the soil.

OPPORTUNITIES FOR EXPANDING ADOPTION OF SOIL HEALTH MANAGEMENT PRACTICES

Participants identified the following opportunities to expand adoption of soil health management practices (listed in order of popularity):

1) Determine both short- and long-term costs and benefits of soil health management systems
2) Reduce tillage and its associated costs (e.g., fuel) in the rotation phase of potato systems
3) Introduce cover crops, and their associated benefits, to the grower community
4) Breed new cover crops for specific qualities related to enhancing soil health (i.e., low growing cover crops with high volume root mass, like dwarf rye)
5) Employ soil health management systems, such as no-till and cover crops, in the rotation phase of the potato system
6) Combine soil health testing for singular interpretation
7) Create a soil health management plan for potato producers
8) Reduce pesticide use & other inputs
9) Identify knowledge gaps about soil-borne pathogens & future threats (i.e., determine the impact of biological amendments, fumigants and chemicals on soil biology and their function)
10) Identify other knowledge gaps and their impacts on potato health and nutrition
11) Integrate land management strategies
12) Identify cash-generating cover crops
13) Soil held at pre-competitive levels
14) Appropriate green manure and cover crops
15) More demonstration fields
16) Provide incentives for adoption
17) Add more biosolids and manure

BARRIERS TO EXPANDING ADOPTION OF SOIL HEALTH MANAGEMENT PRACTICES

Participants identified the following barriers to expanding adoption of soil health management systems (listed in no particular order):

1) Risks & costs to farmers
    a. Short season (cover crop season is too short, high cost)

b. Time & labor costs
c. Perception that adoption of soil health management = higher costs to consumers and society
d. Equipment costs (e.g., no-till drill)
e. Costs to ship and health & safety regulations related to manure
f. Food safety, foreign material presence, and customer approval of low-input varieties
g. Funding needs for long-term projects

2) Lack of education for farmers
    a. Cost of land degradation
    b. How to use cover crops
    c. Understanding soil as a finite resource
    d. Lack of cropping system integration
3) Knowledge gaps
    a. Information flow from academia to growers
    b. Knowledge gaps in belowground soil processes that inhibit soil health test interpretation
    c. Fear that cover crops lead to weeds
    d. Linkage between economic viability and a sustainable production system
4) Defining soil health
    a. Lack of a common soil health definition and system of interpretation for farmers
    b. Lack of a baseline from which to set a goal for improvement
5) Cultural resistance
6) Reliance on and success of pesticides
    a. Herbicide resistant cover crops
    b. Security from fumigation
7) Soil disturbance is necessary for potato production
8) Water
    a. The perception was that cover crops can require more water
9) Reliance on rented land
    a. Business contracts often discourage adoption of soil health processes (i.e. pay less for product with less inputs)

Participants agreed that it is necessary to understand the economic benefits of soil health before adoption of soil health management systems will become widespread. The cost of land and soil degradation is a limiting factor. Farmers need to fundamentally change their underlying assumptions about potato production and soil health. As part of this change, farmers need a step-by-step process for enhancing soil health. "If potato growers could begin to think of themselves not just as potato growers, but also as Carbon managers, then this would lead to different management decisions that would improve soil health, yield, drought resilience, pest suppression, and the long-term sustainability of their operations."

NEXT STEPS

The following volunteered to serve in a working group: Ryan Krabill, Brenda Schroeder, Chris Voigt, Yves LeClerc, Marlon Winger, Noah Rosenzweig, Wayne Honeycutt, AJ Bussan, Karl Ritchie, Pat Kole, and

Heath Gimmestad. This working group will consider the following topics and report back to the larger group:

1) Establishing a network of potato-soil health management system evaluation and demonstration sites that would cross approximately eight regions, multiple soils, and three production scales.
2) Engage the potato industry in developing soil health measurements (Noah, Lisa, Wayne, Marlon) that would consider such topics as:
    a. Developing a standard for evaluation
    b. Identifying the capital involved at a grassroots level that can be scaled to a national level
    c. Closely aligning with Soil Health Institute measurement evaluation/development. Goals to consider include:
        i. Develop a project to nationally deploy soil health measurements
        ii. Include metrics for a measurable result that allows a grower to understand improvements in soil health according to Haney, Cornell CASH, Soil Management Assessment Framework or other tests
        iii. Understand which practices improve soil health
        iv. Establish a baseline for improvement, determine if it needs to be scientific, and determine one measurement to determine improvements in soil health
3) Additional Considerations
    a. Move from easy to difficult for implementation and testing
    b. Identify goals, actionable steps, and provide annual updates
    c. Grow Carbon Bank
        i. Establish diverse, regional-specific cover crops that account for variance in crop rotations, increase nutrient availability and pest suppression, and have large root mass
    d. As an industry, do we want to farm potatoes in such a way that soil health goals are as important as yield and quality goals for potato production?
4) Develop a Soil Health Innovator Program (SHIP) – NSHPC/USA Potatoes
    a. Potatoes USA and state managers in WA, ID, MI, CO, ME, OR, ND, MN, WI, NY
5) Sell the Concept
    a. State and National Level at Expo, PRAC Meeting in Denver
6) Identify Partners and Grower Participants
    a. Partners: Customers, NGO, NRCS, Extension
    b. Grower Participants
7) Identify Additional Needs:
    a. Determine how soil health changes will impact soil borne pathogens
    b. Advance understanding of cover crop research and effect on nematodes while focusing on enhancing soil health
    c. Consider ways to amplify the message through Facebook, YouTube, Instagram, Twitter

REFERENCES

1) PowerPoint Presentations by Wayne Honeycutt and Marlon Winger
2) "Managing for Soil Health when Raising Potatoes - A Farmer's Perspective" by Brendon Rockey http://www.nacdnet.org/soil-champs/southwest/brendon-rockey/
3) Keys to Building a Healthy Soil by Gabe Brown

APPENDIX – List of Participants

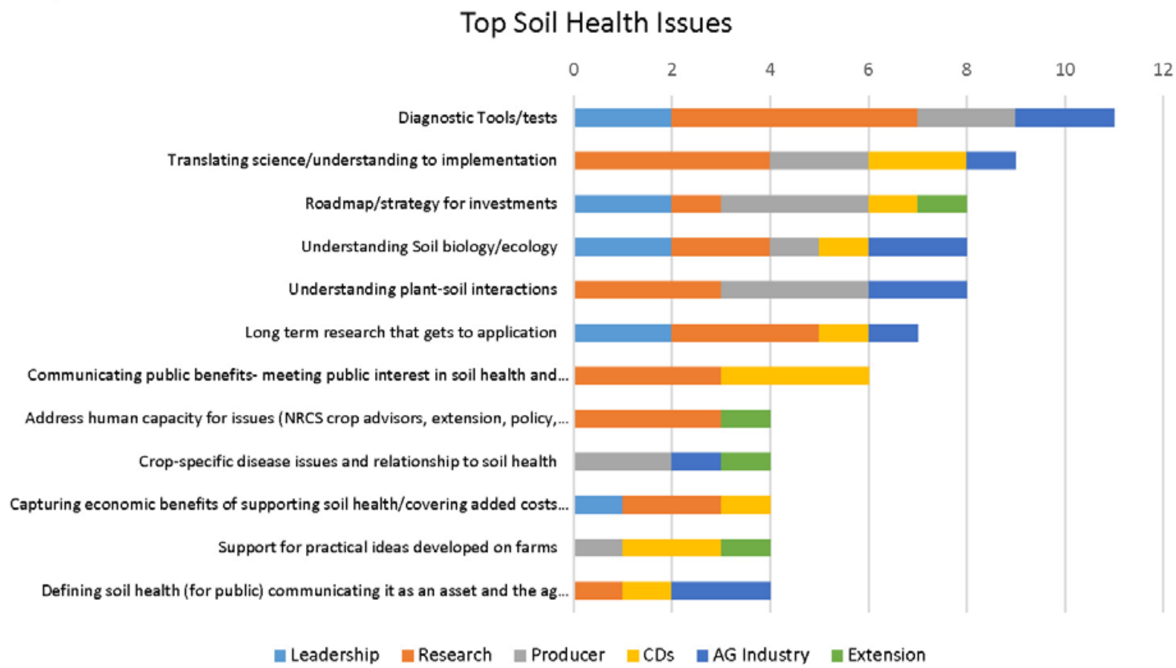
Last Name	First Name	Company/Organization
Bussan	AJ	Wysocki Farms
David	Nick	R.D. Offutt
Ehrlich	Jim	Colorado Potato Administrative Committee
Geary	Brad	Bringham Young University
Gimmestad	Heath	Friehe Farms
Honeycutt	Wayne	Soil Health Institute
Keeling	John	National Potato Council
Kole	Pat	Idaho Potato Commission
Krabill	Ryan	Potatoes USA
LaJoie	Dominic	LaJoie Growers
Larkin	Bob	USDA-ARS
Leclerc	Yves	McCain Foods
McGovern	Keith	R.D. Offutt
Mitchell	Tyler	Mitchell Farms
Plant	Andrew	Maine Potato Board
Rath	Byron	Soil Health Institute
Ritchie	Karl	Walther Farms
Rosenzweig	Noah	Michigan State University
Schroeder	Brenda	University of Idaho
Shafer	Steve	Soil Health Institute
Tiemann	Lisa	Michigan State University
Voigt	Chris	Washington State Potato Commission
Wenkel	Mike	Michigan Potato Industry Commission
Winger	Marlon	USDA- Natural Resources Conservation Service

Appendix B: Report from 2018 Washington Soil Health Summit

WA State Soil Health Summit: Summary Report

Center for Sustaining Agriculture & Natural Resources, Washington State University

Washington State Conservation Commission



Barriers to Progress on Soil Health:

- The most critical barrier is the inherently complex nature of soils – and how little we actually know.
- The lack of clarity and consistency of soil health metrics across the region and cropping systems, and measuring the benefit of improved soil management over time.
- Sociology/psychology of adoption: major barrier is the individual's mindset – particularly as it relates to the difficulty of correlating management investments with measurable outcomes.
- The economic incentive at the farm level is often unclear. We need to better understand ROI (return on investment) of soil management practices.
- The disconnect between producers and consumers as it relates to management of soils. Producers don't get paid to manage soils, they get paid for a crop.

Resources, Tools & Opportunities:

- "Sustainability audits" for various crops.
- Address the dwindling human capacity issue with good hires (i.e. research, extension, crop advisors, agency / CD staffing, etc.).
- Focus on utilizing current resources and create a clearinghouse for new innovation.
- Enhance the research and technical support connectivity between researchers and innovative producers.
- Explore opportunities for accessing data-bases on soils collected by the private sector.
- Further evaluation of various soil health indicators / tests across cropping systems and the region.
- Building a road map for soil health to drive all other soil health investments.

Ideas relating to formal (university) education:

- Add capacity to teach soil health-related courses
- Need a broad base of knowledge, encourage cross-disciplinary training for students (no silos).
- Encourage training in more effective technical communication, (e.g. or soil scientists)
- Re-introduce conservation ethics and add more training in social sciences part of soils courses and standard curriculum.

Develop statewide roadmap across sectors and stakeholders:

- Start with the goals, what is the purpose. What is the end goal and does it differ between systems
- What is SH/what are the factors
- Main impacts on peoples bottom lines
- Timeline (little overlap short-term but more long-term)
- Linking triage goals priorities
- Need buy in

Ideas relating to research:	Ideas relating to extension/implementation:
• Taking data already collected on farm, and analyzing it in meaningful ways to develop regional best practices. (This should be seen as low hanging fruit, but needing some clarity about what the questions are first, think about a comparative score card approach?) • Stable funding pool from state and industry (pooled cross-industry where possible for common issues) to invest in soil health research (drives hires, what people study, esp. given funding at public universities). • Create soil industry directed faculty positions/Industry directed endowed chairs at WSU representing top five crops (cropping systems). • Consider a multi-disciplinary cluster hire to build more scientific capacity and encourage cross/multi-disciplinary collaboration (Incentivize farmer-researcher collaborations). • Support transformational work and long-term projects. Consider mini long term agroecosystem research on top five productive regions in WA. • Basic biology needs to be looked at (plants & soils). • Research repressive soil mechanisms – why some plants don't die when others do. • Pool resources for more money and investment in soil health. Need money to support programs. • Soil health committee funded by commission, support research. • Address facility issues (especially outside of Pullman) - proximity location of university, university has strong attachment to wheat - cannot staff Othello or Prossor research center; Re-org ag research stations (Othello Prosser) to better be able to emulate commercial operations (so there's not as big a gap between research and implementation).	• "*Advances*" type book for other 'cropping systems'. • Create new partnerships in industry and cultivate better partnerships to reach more diverse group of producers to effect change (ones we have not thought of yet, like Cliff Bar). • Central website for information. • Collaboration, resource pooling, and training: farmer-researcher collaborations and interactions (foster two way influences), grower to grower mentoring, education for crop consultants and training. • Communication plan reaching producers where they are with language they understand; Improvements in communications down the supply chain (potential tool example: potato sustainability project). • Encourage 'out of box' work in extension and ag service • Risk assessment tool (e.g. Farm Assist or Home Assist programs established in the 80's: guide a user through protecting water resources that can guide farms through sustainability decisions). • Monitoring should always be part of the protocol to implementing new practices. • How to let farmers know more about the practices that ARE making a difference. • "Cultivating a pioneer culture" –identifying innovators; • Long term demonstration of proven ideas critical for grower buy in. • Finance on farm research with research, growers, industry. • Matching extension with growers willing to do large scale plots/demos. • We really need metrics that are this easy to identify, Develop of use existing studies to better understand SH metrics; Train dogs to identify healthy soil.

Capacity Investments		
	• "The goals of our consumers should be our goals"; Bring more stakeholders (i.e. those who eat) to the table= more $$$ for research. • Discussion of funding to support soil health over time e.g. Soil health checkoff? Fertilizer tax? Carbon tax? Soil erosion tax? Establishing public, private partnerships – successful in Midwest. • Invest in recognizing (award program), validating (replicated studies) and sharing practices that innovative producers are implementing successfully.	• Invest in and fund long-term, on-farm, research and demonstration projects. Involve growers with operations of different scales, researchers, industry. • Invest in dedicated, multi-disciplinary soil health science positions. Fund a dedicated soil ecology center, endowed chairs, with state government leadership and industry support. • Invest in a research and outreach team to collect stories on and market the benefits of soil health to producers and the public.

Regional Strategy Considerations		
	• Invest in standard soil health metrics and methods to evaluate soil health improvements and success that also allow for the unique characteristics that differ across the region. • Need for a shared strategy and leadership, with coordination across the region and across sectors—research, industry, agencies, growers—and with stakeholder buy in (strategic plan/roadmap); Make sure the right players are at the table. • Need to overcome obstacles to forming research collaborations across universities in the region.	• Need to strengthen the links between soil health, resilience, and adaptation capacity in light of climate extremes. • Cropping systems and what are associated baselines – quantify what is being removed; Build on the research strengths in each region (coordination to avoid. duplication of efforts build teams with expertise at the local/regional/systems level). • Where to get the money; How money does or does not cross borders (geographic, agency etc.).

Appendix C: Relation of Soil Health Indicators to Soil Function

Soil health indicators and the processes they affect. (Modified from Lal 2011)

	Soil health indicators	Soil processes affected	Landscape scale
Physical	Soil structure	Aggregate stability, organic matter turnover	Aggregation, surface seal, indication of water and chemical retention and transportation
	Porosity	Air capacity, plant available water capacity, relative field capacity	Soil crusting, reduced seed germination, aeration, water entry
	Infiltration	Soil water availability and movement	Potential for leaching, productivity, erosion
	Bulk density	Soil structural condition; compaction	Volumetric basis for soil reporting
	Soil depth and rooting	Plant available water capacity, subsoil salinity	Productivity potential; uncertain whether trends can be discerned over long time periods
	Soil/plant available water and distribution	Field capacity, permanent wilting point, macropore flow, texture	Water and chemical retention and transportation; yield
	Soil protective cover	Soil water and nutrient movement, soil stabilisation, C and N fixation	Soil physical movement, organic matter input and movement
Chemical	pH	Biological and chemical activity thresholds	Soil acidification, salinisation, electrical conductivity, soil structural stability
	EC	Plant and microbial activity thresholds	Soil structural decline; leachable salts
	Plant available N, P, K	Plant available nutrients and potential for loss	Capacity for crop growth and yield; environmental hazard (e.g. algal blooms)
Biological	Soil organic matter Light fraction or Macro-organic matter Mineralisable C and N	Plant residue decomposition, organic matter storage and quality, macroaggregate formation Metabolic activity of soil organisms, net inorganic N flux from mineralisation and immobilisation	Loss of organic matter, soil aggregate formation Total organic C, soil respiration rate, nutrient supply Microbial activity, nutrient supply
	Soil total C and N	C and N mass and balance	Soil structure, nutrient supply
	Soil respiration	Microbial activity	Microbial activity
	Microbial biomass C and N	Microbial activity	Soil structure, nutrient supply, pesticide degradation
	Microbial quotients	Substrate use efficiency	Substrate quality
	Microbial diversity	Nutrient cycling and availability	
	Other microbiological indicators, enzyme activity	Soil structure, labile carbon, Km, Vmax, Ki, Q10	Biochemical activity, nutrient supply

Appendix D: Related Research

Michigan Potato Soil Health Project (Source: Proceedings of 2016 WA/OR Potato Conference)

Potato Soil Health and Ecology: Experiences from Michigan Potato Production

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Introduction

Potatoes (*Solanum tuberosum*) are purchased as fresh, chipping, frozen, or starch products and tubers must meet a high quality standard in terms of cosmetic and physical appearance from producers. Potato production in Michigan (MI) ranks seventh nationally with a farm gate value of nearly $208 million annually. Approximately 70% of production in the state goes towards the chip processing industry. Over the last decade some MI growers in certain production areas have been experienced declining yields and marketability issues. These quality problems have reduced the marketable output. Many growers have a perception that formerly productive fields are no longer performing to expectations. Nearly 90% of major diseases that impact crops (including potato) are caused by soilborne pathogens. Soilborne disease complexes such as Verticillium wilt caused by *Verticillium dahliae* (Figures 1 and 2) and potato common scab (PCS) caused by *Streptomyces* spp. (Figures 3 and 4) are recognized as a major cause of yield and quality declines. The amount of acreage affected by potato common scab (PCS) caused by *Streptomyces* spp. (Slack, 1992, Loria et al., 1997, Stevenson et al., 2001) continues to be a concern for commercial potato production in MI and is on the rise. Growers in MI believe that soils have suffered from compaction, and intensive use of pesticides and fertilizers, which degrades soil organic matter and reduces microbial diversity vital for maintaining soil health. Though soilborne disease complexes are recognized as a cause of yield and quality declines, soil ecology is not adequately understood. To better understand soil ecology, a soil health project was initiated to expand baseline information about pathogen interaction with biotic and abiotic soil factors.

The activity of microorganism is concentrated in the top layer of the soil that constitutes less than 1% of the total soil volume. Microorganisms in the soil are integral to carbon, nitrogen, sulfur, and phosphorous cycling, decomposition of organic matter, and degradation of waste and pollutants. Additionally, microorganisms affect the physical properties of soil, maintain soil structure, affect water holding capacity and infiltration rate, crusting, erosion and compaction. Bulk soil (the soil outside of the rhizosphere) contains approximately 10,000 bacterial species per gram of soil. The rhizosphere is the zone of soil influence by the roots, can contain as many as three times the diversity of bulk soil. Less than 1% of many of these bacteria can be isolated in the laboratory.   . Many of the soil organisms in the rhizosphere are beneficial to plant health and can have significant impacts on disease control.

Materials and Methods

Web-based grower survey A web-based survey instrument was developed and vetted to determine grower's perspectives and perceptions of important production issues. The purpose of the grower survey was twofold: 1. Identify grower opinion on key factors driving yield reductions in "mature" and "new" potato ground; and 2. Ask growers to suggest fields for soil sampling.

Field sampling In fall of 2012 and early spring of 2013, 22 separate fields with varying levels of potato history were sampled on a grid sampling scheme and analyzed for both biotic and abiotic soil properties including pH, buffer pH, cation exchange capacity, organic matter, calcium, potassium, magnesium, phosphorous, *Verticillium* spp. colony forming units (CFUs)/10 g of soil, root-lesion nematode populations, and soil microbial structure of collected samples using DNA technology. Soil was sampled in the fall/winter of 2012-13. Soil sampling was restricted to 20 fields that were considered to have high and low marketable yields before cropping (12 growers). Sampling locations were GPS marked (20 samples per field) and 400 samples in total were processed at the MSU soil testing lab and sequenced using DNA technology. At the end of the growing season 20 ha sections of fields affected by PCS were harvested in block samples approximately 2 ha in size, each of which yielded 10 aggregated samples/field.

Parallel sequencing Soil from each sample was used for DNA extraction, using the Mo Bio 101 DNA extraction kit (Mo Bio Laboratories Inc., Carlsbad, CA). Soil genomic DNA was used for PCR amplification of the 16S variable regions and samples were sequenced by the Illumina paired-end technique using the previously described protocol (Kozich et al., 2013) with slight modifications for total bacterial community analysis. Samples were sequenced at the MSU Research and Technology Support Facility.

Field mapping ArcGIS (ESRI, Redlands CA) was used to analyze and visually display soil sample and DNA sequencing results. Data for each field was entered into a GIS database and Inverse Distance Weighting (IDW) was used to estimate values between points for soil physical properties, microbial diversity, and yield. IDW assumes that points located closer to each other are more related than those farther apart. This principle can be used to approximate the distribution of data and to understand how soil properties are correlated across space.

Results

Web-based grower survey More than 50% of the growers in MI surveyed indicated that yield has decreased by at least 5% or more over the last decade (Figure 5). Additionally, the amount of acreage affected by potato common scab (PCS) caused by *Streptomyces* spp. increased by 11% or more over last decade (Figure 6). Growers in MI identified that soil microbial activity and diversity are important factors related to soil health and limiting yield (Figure 7).

Parallel sequencing Next generation sequencing targeting the 16S rRNA gene, and dual indexing allowed high throughput processing of samples simultaneously. The total number of taxa identified to phyla, class, order, family and genus was 28, 81, 140, 300 and 814 respectively. Sequencing results and information gathered on yield and scab pressure from each point was used to generate multi-layer GIS-based maps.

Field mapping After all data assembled into a database, each field was examined individually for spatial continuity and variability of the sample points using geostatistical parameters. Data was then interpolated with IDW mapping methods and visual correlations were made between scab severity, yield. and biological and physical soil properties (Figure 8). GIS mapping of soil properties enabled the visualization of relationships between measured variables.

Summary

The procedures and methods developed during this study will be used to build a framework on which to construct tools for understanding microbial interactions within soil as well as visualizing pathogen levels across fields as part of an integrated pest management system. These interactions between plants and microorganisms are a growing field of study for plant pathologists and the American Phytopathological Society has organized a worldwide phytobiome initiative which targets an understanding of how the associated microbial community influences or is influence by the plant and how that information can be used to improve crop productivity (www.phytobimes.org). Soil microorganisms respond quickly to changes, and rapidly adapt to environmental conditions and stress. Changes in microbial populations or activity can precede detectable changes in soil physical and chemical properties. Because microbes serve as indicators of soil health an Increased understanding of plant-associated microorganisms will lead to better management of soil health. This project was used to develop baseline data on soil interactions to serve as a foundation for future research to improve soil ecology in Michigan potato fields and strengthen Michigan's potato industry's competitive position by increasing yields.

Soil health and soil ecology has become a focus of the potato pathology laboratory at Michigan State University and the Michigan Potato Industry. As new molecular tools become available and costs decrease, the ability to understand the soil molecular ecology will increase. These molecular tools along with geostatistical and geographical tools have aided researchers in looking at soil ecology from a whole field perspective. The long-term goals of these projects include using the baseline data to develop a trans-disciplinary tool combining DNA technologies, GIS and computational biology at the subfield management scale so that growers can easily monitor soil conditions, soil biodiversity, and pathogen levels. Additionally, the development of DNA based detection to map specific soil-borne pathogens of potato. The hope is to incorporate predictive and conditional probability maps into integrated soil borne disease management in commercial potato production. This technology will improve productivity, reduce chemical inputs, and improve soil quality for disease-free and sustainable high-quality crop production.

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Enhancing Soil Health in U.S. Potato Production Systems

A large multi-state project was funded in 2018 through the Specialty Crop Research Initiative of the USDA. This project is a collaboration between researchers located in numerous states (Minnesota, Michigan, Wisconsin, Colorado, Montana, North Dakota, Oregon, Idaho, Washington, Maine) and seeks to "establish physical, chemical, and biological indicators of soil health for sustainable potato production." Experimental sites in the PNW will be located at the Hermiston Agricultural Research and Extension Center (OR) and at Miller Research in Rupert, ID. On-farm observational/gridded sampling will take place in OR, ID, and WA. The following novel contributions were described in the project proposal:

Our goal is to develop the following products through this project:

1. *Nationally validated soil-testing assays suitable for detection of soilborne pathogen inoculum levels, beneficial microbes and soil physicochemical characteristics. Protocols will be developed to evaluate impacts of rotation (length and crop type), crop inputs (conventional and biological) on disease incidence and severity and soil health.*

2. *Improved epidemiological and economic models useful for management recommendations for soilborne disease management, with emphasis on how to interpret the results of soil health tests.*

3. *Identification of a customizable system of specific best management practices. Identification of target-specific cover crops, rotations and biological activity correlated with reducing disease and increasing soil health.*

We will also develop these actionable research-based recommendations for the potato industry:

1. Methods to evaluate current regional specific potato grower management operations based on soil health indicators, including information on economic thresholds for short- and long-term adoption of best management practices.

2. Information to establish a national soil health database on potato soils; develop a soil health roadmap to promote and adopt soil health testing through delivery of educational programs.

3. Tools for enhanced soil health, soilborne disease and soil management for sustainable potato production and soil stewardship.

Strengthening Soil Health to Suppress Verticillium Wilt in Potato Systems

This project was begun in 2017 with funding from the Northwest Potato Research Consortium and led by Markus Kleber at OSU is focused on understanding the management practices and soil properties that reduce the severity of the Verticillium pathogen in three regions: the Snake River Plain in Idaho, the Columbia River Basin in Oregon and Washington, and the Klamath Basin in Oregon, with an expected 40 fields sampled. Potato fields that growers report as being "severely" impacted or having a "high" amount of Verticillium will be compared with "healthy" or "low" wilt fields. Information about the management history of these fields for the past five years is also being collected. At the time of writing, there were no results available for this project.

Madison County Healthy Soil Initiative

This SARE professional + producer project in eastern Idaho followed yields, costs, and grower impressions on farms that adopted soil health practices (Taylor 2016). The project report is available here:

https://projects.sare.org/project-reports/ow15-032/

Appendix E: Research on Related Topics Funded by PNW Potato Research Consortium or Washington State Potato Commissions

Projects prior to 2011 were funded by the Washington Potato Commission; 2011-2018 listings include projects from Washington, Oregon and Idaho funded by the PNW Potato Research Consortium

2018: Soil-Fumigation: Discovery, Application, and Alternatives

2017: Nematode management in the face of short telone and vydate

2016: Dickeya and Pectobacterium spp. Tuber Soft Rot, Blackleg and Stem Rot

2016: Potato Soil Health and Ecology: Experiences from Michigan Potato Production

2016: The Pathogen that Causes Verticillium Wilt of Potato, Verticillium dahliae, Infects and Alters Biomass of Several Rotational Crops

2015: Management of Pythium Leak

2015: Managing the Elusive Potato Black Dot Pathogen, Colletotrichum coccodes

2014: Scheduling Fungicide Applications for Late Blight Management in the Columbia Basin of Washington and Oregon

2014: Seed Piece Decay: Proven Management Practices

2014: Verticillium dahliae Infects Specific Rotational Crops of Potato in the Columbia Basin, WA

2014: Epidemiology and Management of Powdery and Common Scab in the Columbia Basin

2014: Bacterial Ring Rot: Review of Biology and Management

2013: Effect of Extended Crop Rotation on Incidence of Potato Black Dot

2011: Impact of Soil Conditions on the Ability to Control Verticillium Wilt of Potato in the Lower Columbia Basin

2011: Soil Amendments, Manure vs. Compost

2010: WSDA’s Implementation of the Soil Fumigant Mitigation Measures

2010: Microbial Control of Potato Tuberworm in Potato Plants and Tuber Storage with Emphasis on Research Conducted in the Pacific Northwest of the United States

2009: Relative roles of tuber and soilborne inoculum in the development of Verticillium wilt in the potato cultivar “Russet Burbank”

2009: Rhizoctonia Disease of Potato: The Soil That Won't Wash Off

2007: Development and Management of Bacterial Stem Rot in the Columbia Basin

2005: Reduced Tillage in a Three Year Potato Rotation

2005: Managing Potato Late Blight in the Columbia Basin –The Basics

2003: Adopting Conservation Tillage in Irrigated Cropping Systems

2002: Epidemiology and Management of Sclerotinia Stem Rot

2000: SOIL AND PETIOLE NUTRIENT MONITORING

1998: Management of Meloidogyne chitwoodi Using Green Manure and Cover Crops and Nematicides, and Control of the Corky Ringspot Disease on Potato, 1997

1998: Some Aspects of the Volunteer Potato Problem

1998: Tillage and other Practices for Volunteer Suppression

1995: Green-Manured Winter Cover Crops in Irrigated Potato Rotations

1993: SOIL FUMIGATION AND SOIL BORNE DISEASES OF POTATO

1992: Growth and Development of Potato Root Types: Implications for Placement and Timing Strategies in Fertility Management

1992: Calculating a Soils Percent of Water at Field Capacity and the Percent of Field Capacity

1991: Cover Crops and Their Effects on Disease Control and Yield

1991: Deep Tillage Effects on Potato Yield and Quality

1989: Soil Fertility and Water Management Relationships In Potato Production

1989: Cropping Practices and Potato Early Dying

1987: From Soil Sample To Fertilizer Recommendation

1987: Effect of Previous Cropping on Verticillium Dahliae Control and Potato Production

1985: Reservoir Tillage For Center Pivot Irrigation

1984: The Effects of Soil Fumigation on the Nitrogen Nutrition of Potatoes

1984: Materials For Soil Fumigation - Characteristics, Availability, Application Methods

1979: Minimum Tillage for Potatoes -- Some Commercial Economics

1978: Mini Till As A Farmer Does It

1978: Minimum Tillage Potatoes -- Some Economics

1977: Minimum Tillage Potato Panel

1977: Potato Minimum Tillage Panel

1977: Mechanics of Minimum Tillage Potato Planting

1977: Turnips As a Rotation Crop

1976: Minimum Tillage for Potatoes

1975: Minimum Tillage For Potatoes

1974: Effect of continuous and Discontinuous Soil Fumigation With Vine Burning on Control of Verticillium Albo-Atrum of Potato

1974: Chloropicrin Soil Fumigants - A Possible Fertilizer Substitute

1974: Compact Soil -- Could It Be Part of the Problem?

1974: Fumigation Incentives in Potato Contracts

1973: Fumigants, Rates, and Fumigation Methods Affecting Verticillium Wilt Control and Potato Yields

1971: Effect of Annual Soil Fumigation and Annual Preharvest Vine Burning On Control of Verticillium

1971: Factors in Fumigation Failure

1969: The Influence of Nitrogen on Straw Decomposition in the Field and Laboratory

1969: Effect Of Three Years Fumigation And Burning of Vines on The Control of Verticillium Wilt in Russet Burbank Potato

1967: What Soil Variability Means To The Potato Industry

1967: Effect Of Soil Temperature Following Fumigations On Verticillium Wilt Delay And Yield Increase

1967: Effect Of Fumigants and Other Chemicals on Yield of Potatoes On Verticillium Wilt Infested Soils

1966: Principles of Soil Fumigant Diffusion

1966: 1964-1965 Soil Fumigation Results On Verticillium Wilt Control

1966: Critical Factors For Successful Soil Fumigation

1965: Crop Rotation As A Means of Controlling Northern Root Knot Nematode in Washington

1964: Potash Fertility And Blackspot

1964: Weeds In Management Planning

1963: Effects Of Soil Fumigation On Yield And Quality Of Russet Burbank Potatoes In The Columbia Basin Of Washington

1963: Soil Fumigation For Nematode Control

1963: Crop Rotation - Can They Effectively Control Potato Diseases?