Use of Crop Rotations, Cover Crops and Green Manures for Disease Suppression in Potato Cropping Systems

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ABSTRACT

Crop rotations and the inclusion of cover crops and green manures are primary tools in the sustainable management of soil-borne diseases in crop production systems. Crop rotations can reduce soil-borne disease through three general mechanisms: (1) serving as a break in the host-pathogen cycle; (2) by altering the soil physical, chemical, or biological characteristics to stimulate microbial activity and diversity; or (3) directly inhibiting pathogens through the release of suppressive or toxic compounds or the enhancement of specific antagonists. Brassicas, sudangrass, and related plant types are disease-suppressive crops well-known for their biofumigation potential but also have other effects on soil microbiology that are important in disease suppression. The efficacy of rotations for reducing soil-borne diseases is dependent on several factors, including crop type, rotation length, rotation sequence, and use of the crop (as full-season rotation, cover crop, or green manure). Years of field research with Brassica and non-Brassica rotation crops in potato cropping systems in Maine have documented the efficacy of Brassica green manures for the reduction of multiple soil-borne diseases. However, they have also indicated that these crops can provide disease control even when not incorporated as green manures and that other non-biofumigant crops (such as barley, ryegrass, and buckwheat) can also be effective in disease suppression. In general, all crops provided better disease control when used as green manure vs. as a cover crop, but the addition of a cover crop can improve control provided by most rotation crops. In long-term cropping system trials, rotations incorporating multiple soil health management practices, such as longer rotations, disease-suppressive rotation crops, cover crops, and green manures, and/or organic amendments have resulted in greater yield and microbial activity and fewer disease problems than standard rotations. These results indicate that improved cropping systems may enhance productivity, sustainability, and economic viability.

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1. Introduction

Soil-borne diseases present major problems, affecting the yield and quality of a wide variety of food and crop production systems. Soil-borne pathogens that cause plant diseases encompass a variety of microorganisms, including fungi, bacteria, viruses, and nematodes, with some of the most important and abundant pathogens being pathogenic species of fungi and oomycetes in such genera as *Rhizoctonia, Fusarium, Verticillium, Sclerotinia, Pythium*, and *Phytophthora* [1,2]. These pathogens can often survive in soil or plant debris for many years. Management of soil-borne pathogens and the diseases they cause generally involve multiple approaches to reduce pathogen populations, interfere with their disease-causing activity, or mitigate the disease response in the host plant. The most effective management occurs when soil-borne pathogens are excluded from an area or when disease-resistant host varieties or cultivars have been developed, but these options are often not available [1,3]. For many pathogens, chemical controls can be effective, but for many others, available chemical controls are not very practical or effective. Even where chemical controls are available and feasible, they can be costly and potentially have other issues, such as causing ecological disturbances, human health hazards, damage to aquatic ecosystems, and loss of beneficial microorganisms [1]. For most soil-borne pathogens, alternative or supplemental management approaches are needed.

Cultural management approaches developed from a soil health perspective involving crop rotations, cover crops, and green manures can provide a structural basis for reducing soil-borne pathogens and diseases. These practices have been shown to significantly affect soil physical, chemical, and biological properties [4-9], improve soil water management and reduce erosion [5,6], as well as reduce soil-borne diseases and increase crop productivity [10-12]. Such cultural management approaches are firmly based on the concepts of soil health, and when combined with other disease management practices can result in the more sustainable and practical management of soil-borne diseases.

Potato (*Solanum tuberosum* L.) is an important food crop throughout the world. Several soil-borne diseases, including stem canker and black scurf (caused by *Rhizoctonia solani*), common scab (caused by *Streptomyces scabies*), powdery scab (caused by *Spongospora subterranea*), Verticillium wilt (caused by *Verticillium dahliae*), and white mold (caused by *Sclerotinia sclerotiorum*) are persistent, recurrent problems in potato production, resulting in reduced plant growth and vigor, lower tuber quality and reduced yield [3,13]. In addition, potato is a crop that can be particularly hard on soils due to traditionally short rotations, extensive tillage, minimal crop residue, and minimal crop diversity, resulting in degraded soil health and reduced productivity [6].

This article will provide a brief review of the use of crop rotations, cover crops, and green manures for the reduction of soil-borne diseases in crop production systems. Although the principles presented can be applied to any cropping system, most of the specific examples presented will be from the author's own research dealing with soil-borne diseases in potato production systems.

2. Soil Health

Soil health can be defined as the continued capacity of soil to function as a vital living system to sustain biological productivity, maintain environmental quality, and promote plant, animal, and human health [14]. The health of soils determines agricultural sustainability and environmental quality and greatly affects plant, animal, and human health [14]. With soil health, emphasis is on the importance of all the multiple functions of soil, i.e., biomass production, nutrient cycling, filtering and buffering, water storage/availability, biological habitat, source of biodiversity, etc. Because soil health represents the culmination of many factors, it encompasses virtually all aspects of the physical, chemical, and biological attributes of soil [14,15]. We know that building and maintaining soil health is essential to agricultural sustainability and ecosystem function.

Addressing soil as a vital living system is a key component of soil health, and along with this goes a fuller appreciation of the critical importance of soil biology and microbiology to all aspects of soil health. Soil microbiology, in particular, has been generally neglected or ignored in the management of soils in the past. An active, diverse soil microbiology is necessary for decomposition, nutrient cycling and availability, soil structure,

breakdown of toxins, and suppression of pathogens and diseases [10]. In essence, soil microorganisms are the workhorse of soil and are primarily responsible for accomplishing the various functions of soil. Thus, managing soil health is largely a matter of maintaining a suitable habitat for the organisms that make up the soil biology. Organic matter is the primary food source for microorganisms, and thus, managing organic matter is an important component of soil health. Diverse soil microbiology is promoted by a diversity of plants and plant types, releasing different sets of organic compounds and interacting with different assemblages of microorganisms [16,17]. An active, diverse soil microbiology also helps keep pathogen populations in check and interferes with their ability to cause disease.

Soil health is particularly critical in agroecosystems, where soils can be degraded by intensive cropping practices, resulting in losses in resilience, productivity, sustainability, economic viability, and environmental quality. Strategies for maintaining and improving soil health should focus on managing organic matter, minimizing disturbances, diversifying soil biota, maintaining living plants, and maintaining soil cover [5,8-10].

2.1. Soil Health and Disease Management

Management of soil-borne diseases is closely related to soil health. Soil-borne diseases tend to be most severe when soil conditions are poor due to such things as inadequate drainage, poor structure, low organic matter and fertility, high soil compaction, or low microbial biomass and activity [11]. Most practices that address these issues and improve soil health will also reduce soil-borne diseases. Improved conditions for crop growth generally result in lower disease. Increases in microbial biomass, activity, and diversity can result in a general suppression of disease and potential increased populations of antagonists to pathogens [18]. In addition, specific disease-suppressive practices and strategies can be implemented for further disease suppression.

Crop management practices that are most closely associated with improving soil health as well as reducing soil-borne diseases include the use of crop rotations, cover crops and green manures, organic amendments, and conservation or reduced tillage [8-12]. Each of these practices has been shown to have some beneficial effects on building or maintaining aspects of soil health in various systems [10,19,20].

2.2. Soil Health Management Practices

2.2.1. Crop Rotation

Crop rotations provide numerous benefits to crop production and soil health and serve multiple functions. They can help conserve, maintain, or replenish soil resources, including organic matter, nitrogen, and other nutrient inputs, and physical and chemical properties [5,8-10,21-23]. Crop rotations have been associated with increased soil fertility, increased soil tilth and aggregate stability, improved soil water management, and reduced erosion [5,6], as well as with increasing soil microbial biomass, activity, and diversity due to different types of plant species being present and active in the soil [16,17,24]. However, probably the most important function of crop rotation is its role in disease management. Crop rotations are essential to maintain crop productivity and reduce the buildup of soil-borne plant pathogens and diseases, which can devastate crops grown in multiple consecutive years [25,26].

Several factors are important in determining crop rotation effects on soil health properties and characteristics, including crop type, rotation length, rotation sequence, and how the crop is used. Crop type refers to the class, family, or group of plants the rotation crop belongs to, and there can be substantial differences among types of rotation crops in their effects on soil properties, all the way down to the species and cultivar level [16,27]. In general, crop species that are not a host to the same pathogens and pests as the primary crop can be useful as a rotation crop. However, it is generally best to utilize crops with different characteristics or provide benefits that are not present in the main crop. For example, with potato, which does not provide much organic matter or have an extensive root system, rotation crops that provide these characteristics are preferred, such as grain and grass crops. Rotation length, being the number of years or different crops between main crops, is also important, and generally, longer rotations are better for soil health by providing more different crop types over longer periods [5,26,28]. Rotation sequence, or what crops precede or follow other crops, becomes important in rotations of 3 or more years, with successive crops needing to be compatible with each other and with the rotation crop

immediately preceding the main crop being of primary importance [5,29]. Use of the crop refers to whether the crop is grown as a full-season production crop, as a cover crop, or as green manure, with each use having different characteristics and effects on soil characteristics. The use of a diverse mix of different types of rotation crops increases microbial biomass, activity, and biodiversity and has been associated with further reductions in soil-borne diseases [18,26,30]. With crop rotations, generally the longer amount of time and the more types of crops used between occurrences of the primary host crop, the better it is for disease management (i.e., three- or four-year rotations are known to provide better disease control than two-year rotations, etc.) [26-28,30,31].

2.2.2. Cover Crops and Green Manures

A cover crop can be defined as a crop grown primarily to cover the soil in order to protect it from soil erosion and nutrient losses between periods of crop production [32]. Benefits and uses of cover crops, including reduction of water runoff and soil erosion, the addition of organic matter, improved soil structure and tilth, addition and recycling of nitrogen, greater soil productivity and weed, pest, and disease control, have been previously documented and reviewed [32-36]. Crops grown as green manures can be considered a particular type of cover crop. Green manures refer specifically to the incorporation of fresh plant material for the purpose of soil enrichment [37]. Thus, green manure crops are grown solely to be incorporated into the soil as organic matter while still fresh and green. Green manures generally result in more significant organic matter inputs than traditional crop rotations or cover crops, improving soil fertility and structure [5,38-41]. Green manures also result in increased microbial biomass and activity [42-44], as well as significant changes in soil microbial community characteristics [45-47], but they also change microbial communities in ways that are distinctly different from other types of organic matter amendments [48,49].

2.2.3. Organic Amendments and Conservation Tillage

Although not specifically addressed in this review, other important soil health management practices include organic matter amendments, such as composts or manures, and reductions in tillage through reduced tillage or no-till operations. Organic amendments improve soil structural stability primarily through increases in aggregate stability and improvements in bulk density, aeration, porosity, and water movement, as well as increasing microbial activity [50-55]. Composts and other organic amendments have been shown to reduce soil-borne diseases in many systems, as well as increase yield, although efficacy varies based on many factors [56-62]. Tillage accelerates the breakdown of crop residues and loss of soil organic matter and interferes with soil structural stability [63]. Thus, reduction of tillage through reduced or no-till systems have been shown to increase available water capacity, porosity, aggregate stability, and reduce bulk density [64-68]. Conservation tillage has also been associated with increases in microbial activity and, in some cases, reduced soil-borne diseases [69-71].

3. Disease-Suppressive Rotation Crops

In general, crop rotations (including cover crops and green manures) can reduce soil-borne pathogens by any of three general mechanisms: (1) by serving to interrupt or break the host-pathogen cycle of inoculum production, growth, or survival; (2) by altering the soil's physical, chemical, or biological characteristics, making the soil environment less conducive for pathogen development or survival (often by stimulating microbial activity and diversity or the growth of plant-beneficial microbes); and (3) by direct inhibition of pathogens, either through the production of inhibitory or toxic compounds in the roots or plant residues or by stimulating specific microbial antagonists that directly suppress pathogen inoculum [10,27]. Any crop species that is not a host to the same pathogens as the primary crop can be used as a rotation crop and provide some reduction in soil-borne pathogens via the first mechanism. However, a serious limitation to this mechanism is that most soil-borne pathogens can survive many years in the absence of a host, longer than is feasible for most rotations. Thus, for crop rotations to be more effective as a disease management tool, the second and third mechanisms (which involve the active suppression, reduction, or destruction of pathogen propagules, survival, and disease-causing activity) need to be more fully explored and implemented [10,27].

Those crops and rotations that play an active role in reducing diseases can be referred to as disease-suppressive. A particular type of disease-suppressive crop produces compounds that break down to release

volatile toxins that can suppress soil-borne pathogens and diseases through a process referred to as biofumigation [72,73]. Crops in the Brassicaceae family, which include broccoli, turnip, radish, canola, rapeseed, and mustards, are the predominant biofumigant crops, but some other crops, such as sudangrass and sorghum-sudangrass hybrids, *Crotalaria* spp., and some other plant groups also produce biofumigant compounds [72]. Much research has been done to show the activity and efficacy of biofumigant disease-suppressive crops for the reduction of soil-borne plant pathogens, as well as nematodes and weeds [74-80]. In addition, these types of plants also have unique effects on soil microbial communities that may be related to disease suppression [27,46,81,82].

Another way crop rotations can be used for disease management involves stimulating and manipulating soil microbial communities. Plants are a primary driver of changes in soil microbial communities, and recent studies have documented the effects of crop rotations on microbial communities [29,83-85]. Grass and forage crops with extensive root systems grown as rotation or cover crops are known to increase microbial populations, activity, and diversity, and may also suppress diseases [17,86-88]. Because crop rotations, cover crops, and green manures can dramatically affect soil microbial communities [16,17,89,90], the use of specific crops for their effects on soil microbial communities and the development of disease-suppressive soils is a viable approach to disease management, sometimes referred to as active management of soil microorganisms [17,24,91-93].

In many cases involving disease-suppressive rotations, a definite association between soil microbiology and disease suppression has been observed, and even with biofumigant crops, soil microbiological effects have often been distinct from any direct biofumigation effects. The strong association for the role of soil microbiology in disease suppression has been well documented. In cases with green manures and seed meals, disease control has been observed to be achieved with residues that have no direct anti-microbial activity [46,82,94]. In some cases involving biofumigants, disease suppression was observed to increase long after the activity of the biofumigants has been lost [95-97], or disease control was not related to glucosinolate (biofumigant compound) production [82,98,99]. There are also many examples where disease suppression only functions in a biologically active system [95,100,101]. In some of these cases, the microbial groups that have been associated with the suppression observed have been identified [49,81,102-105]. These observances all indicate the importance of the soil microbial communities in disease suppression. Biofumigant disease-suppressive crops may be particularly effective because they combine multiple mechanisms of action, the direct biofumigant effect on pathogens, along with additional effects on soil microbial communities that result in improved disease suppression. Thus, even when conditions are not optimal or conducive for biofumigation, disease suppression may still be observed due to these additional microbiological effects.

4. Use of Disease-Suppressive Rotation Crops in Potato Production Systems

A variety of crops can be considered disease-suppressive in potato rotations. In addition to the various Brassicaceous and sudangrass biofumigant crops already mentioned, many non-biofumigant crops have also been shown to reduce soil-borne disease in potato rotations. These include such crops as ryegrass, buckwheat, barley, and winter rye. From our own research, there are several examples where non-biofumigant crops reduced soil-borne diseases comparably to biofumigant green manures in trials conducted in commercial grower's fields in Maine with a history of soil-borne disease problems. In one series of trials [94], a ryegrass rotation crop reduced three different soil-borne tuber diseases (common scab, powdery scab, and black scurf) as well as or better than a high-glucosinolate mustard blend and other Brassica green manures, reducing disease incidence by 31-87% (Figure **1A**). In a different grower's field, a buckwheat rotation crop reduced common scab and powdery scab comparably to that of a high-glucosinolate mustard blend, with reductions of disease incidence of 31-53% (Figure **1B**). Buckwheat has also been shown to reduce soil-borne diseases in some other systems as well [106].

In a trial assessing different rotation crops in a 2-year rotation with potato and the presence or absence of a winter rye cover crop [27], in addition to differences among the rotation crops, the presence of the winter rye cover crop reduced the severity of black scurf across all rotation crops by an additional 12 to 20%, resulting in total reductions of 30-45% in the most effective rotations (Figure **2**). Similar effects were also observed for common scab, with the addition of a winter rye fall cover crop reducing common scab severity across all rotations relative
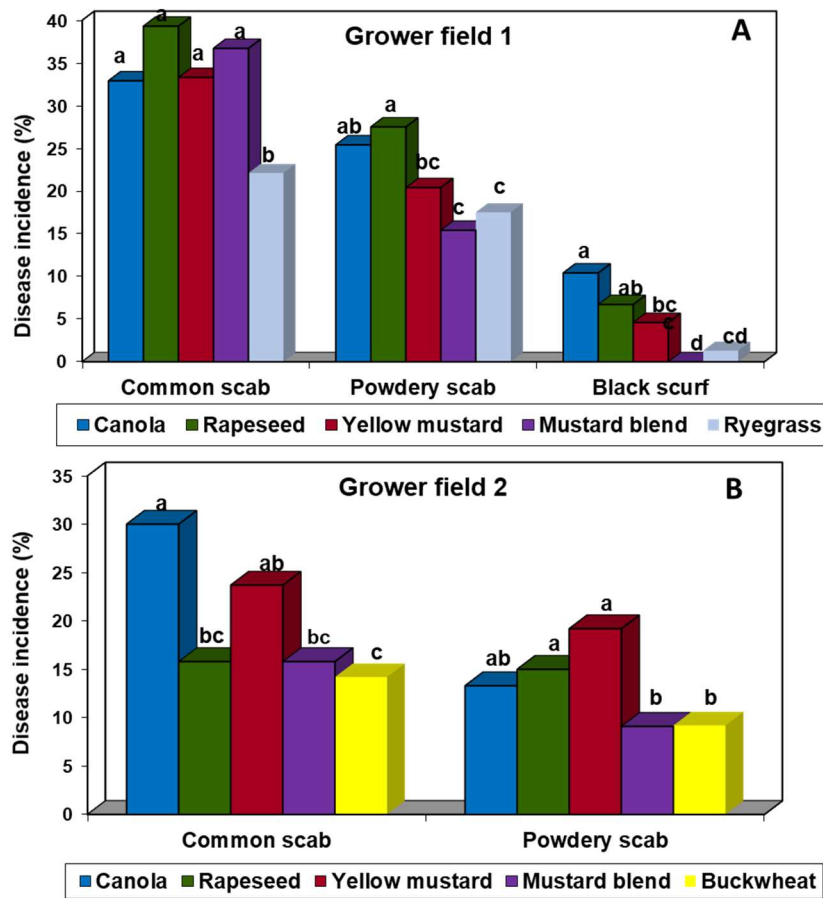
Figure 1: Effect of different rotation crops on the incidence of tuber diseases in the subsequent potato in two commercial grower's fields in Maine. A) Grower field 1 and incidence of common scab, powdery scab, and black scurf; B) Grower field 2 and incidence of common scab and powdery scab (Adapted from Larkin and Lynch 2018 [94]). Bars topped by the same letter within each disease group are not significantly different based on Fisher's protected LSD test (P=0.05).
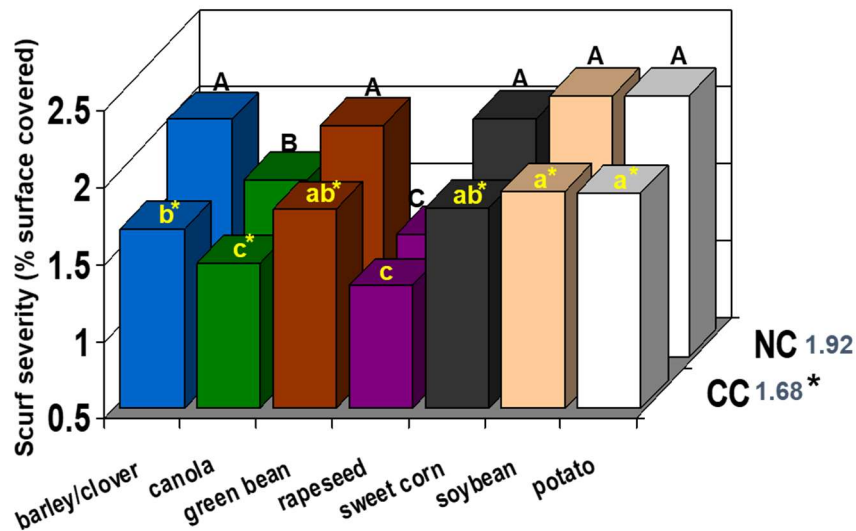

Figure 2: Effect of different rotation crops with and without an additional fall cover crop of winter rye on the severity (% tuber surface covered) of the tuber disease black scurf on the subsequent potato crop averaged over three potato cropping seasons (3-yr mean values) in research trials (Adapted from Larkin *et al*. 2010 [27]). NC=No cover crop, CC=With winter rye cover crop. Bars topped by the same letter within each row are not significantly different based on Fisher's protected LSD test (P=0.05). CC Bars (or values) with an asterisk (*) represent a significant reduction relative to the corresponding NC bar or value.

to no cover crop [27]. Other studies have also shown reductions in soil-borne diseases with the addition of different fall cover crops [19,20,23]. In assessing the suppression of common scabs in Wisconsin potato fields, Lankau *et al*. [107] concluded that management effects were mostly indirect and mediated primarily by their effects on soil microbial communities.

The effects of crop sequence can be observed in a trial of different 3-year rotation combinations assessed over a 3-year production period [29]. Incidence of black scurf was highest when red clover, soybean, or potato was the crop preceding potato. However, when soybean was included in the rotation but did not precede potato (such as with soybean-canola or soybean-barley rotations), disease incidence was much lower (Figure **3**). The lowest disease was observed when canola was the crop preceding potato (soybean-canola and sweet corn-canola). When the rotation contained the same crops but a different sequence, as with canola-sweet corn and sweet corn-canola, the incidence of black scurf was significantly lower for the sweet corn-canola sequence than the canola-sweet corn sequence (Figure **3**). All of this emphasizes the importance of the rotation crop immediately preceding the primary cash crop, in this case, potato. The presence of a disease-suppressive crop preceding potato can substantially reduce soil-borne diseases and have also resulted in increased potato yield [10,12,20,23,47].
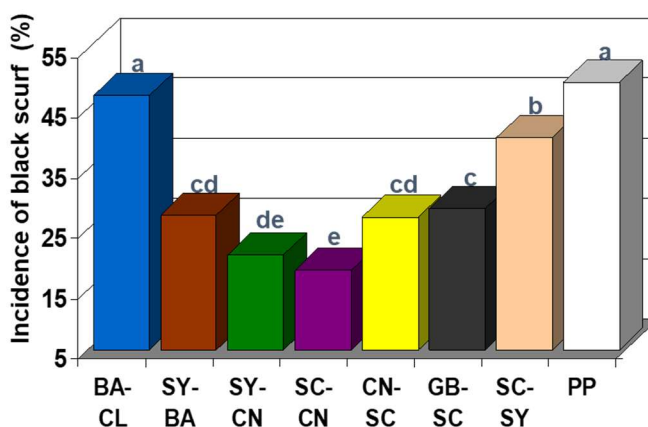

Figure 3: Effect of different crop rotation sequences (3-yr rotations) on the incidence of the tuber disease black scurf on the subsequent potato crop averaged over three potato cropping seasons (Adapted from Larkin and Honeycutt 2006 [29] plus additional data). BA=barley, CL=red clover, SY=soybean, CN=canola, SC=sweet corn, GB=green bean, PP= continuous potato (no rotation). All rotations included potatoes in the third year of the rotation. Bars topped by the same letter are not significantly different based on Fisher's protected LSD test (P=0.05).

Even after the efficacy of different disease-suppressive rotation crops has been established, how to best utilize those crops within a productive cropping system is a major concern. Because the biomass from biofumigant and other crops grown as green manures are turned into the soil, one of the significant disadvantages of using these as a growing season rotation crop is that it takes the field out of production for a revenue-producing crop. Thus, in many areas, these green manure crops are used in the fall following a regular-season rotation crop. However, in areas with short growing seasons, such as in Maine and Canada, these types of crops (and particularly Brassica crops) have not been very successful as fall-planted green manure crops due to the lack of adequate biomass produced in the cool fall months. In our trials in Maine, it was determined that a fall Brassica green manure needed to be planted no later than around August 1 in order to provide effective fall biomass prior to incorporation [108].

To better determine how to best utilize Brassica disease-suppressive crops in cropping systems in the Northeast, we conducted a series of trials assessing different ways to manage known disease-suppressive crops, based on the amount of incorporation of green biomass [108]. Many Brassica crops can be grown for seed or as a production crop, harvested, and then residues remaining after harvest incorporated. In these trials, five different crops, including the disease-suppressive crops mustard blend, rapeseed, and sudangrass, soybean (as a non-suppressive control), and barley/clover (as a standard rotation crop), were each grown and managed in four different ways, ranging from as a pure cover crop (not harvested, not incorporated) to a full green manure (all

biomass incorporated green) and as two variants of a harvested crop (tops harvested, remaining residue incorporated, and tops harvested, residue not incorporated).

Results showed that management practice significantly affected both yield and disease severity of the subsequent potato crop across all rotation crops, with crops managed as green manures resulting in higher tuber yield and lower severity of soil-borne disease than all other practices (Figure **4A** and **B**). However, when grown as a harvested crop and then the residue incorporated, there also was a significant increase in yield relative to when grown as a cover crop only, as well as a reduction in soil-borne disease relative to the harvested but not incorporated treatment. These effects were less than those observed with the full green manure but still significant and represented an intermediate effect when grown for harvest and residues incorporated rather than full biomass. It is notable that this effect was observed for all crops and not just for the biofumigant green manures [108]. When assessed by rotation crop, the mustard blend provided the overall highest tuber yield, significantly greater than soybean or barley, and all three disease-suppressive crops also reduced the severity of black scurf relative to the two non-suppressive crops (Figure **4C** and **D**).
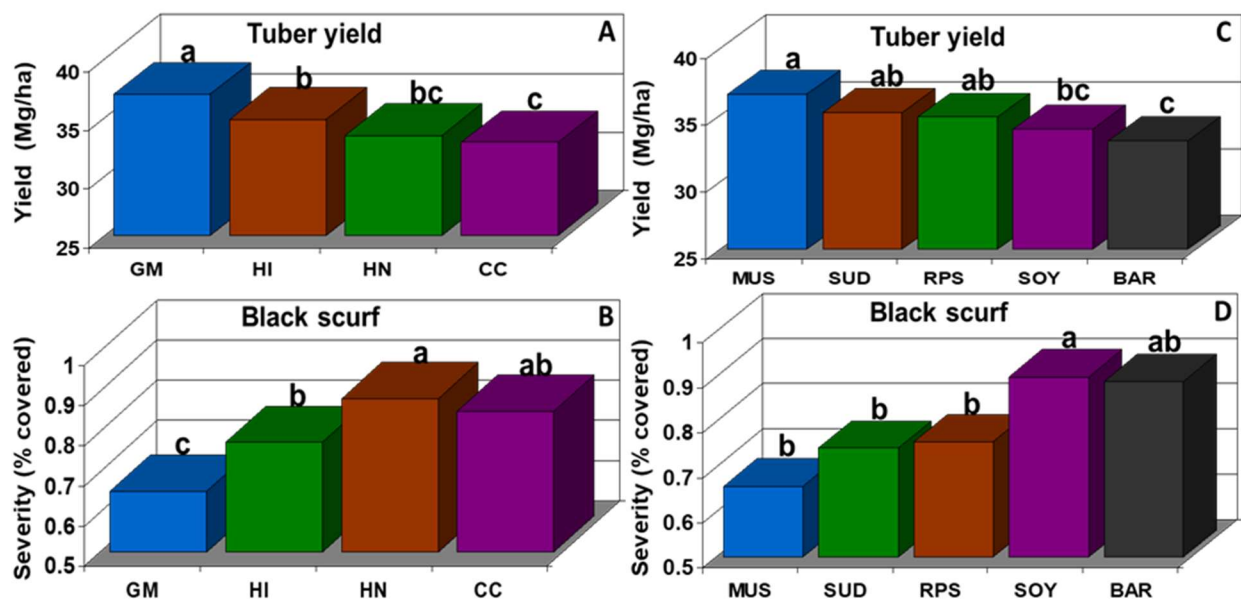

Figure 4: Effect of management practices (A, B) representing different levels of rotation crop residue incorporation and rotation crop type (C, D) on potato tuber yield (A, C) and severity of the tuber disease black scurf (B, D) in the subsequent potato crop in 2-year rotations averaged over two potato cropping seasons (adapted from Larkin and Halloran 2014 [108]). Management practices: GM=green manure (all biomass incorporated green), HI=harvested crop (aboveground biomass removed) remaining stubble incorporate, HN=harvested crop remaining stubble not incorporated, CC=cover crop only, not incorporated. Rotation crops: MUS=Caliente Mustard Blend, SUD=Sudangrass, RPS='Dwarf Essex' rapeseed, SOY=soybean, BAR=barley/clover. Bars topped by the same letter within each graph are not significantly different based on Fisher's protected LSD test (P=0.05).

When the effects of both factors (management practice and rotation crop) are combined, it is clear that the mustard blend crop resulted in the greatest tuber yield overall, with yield increases of 20 to 25% when grown as a green manure over that of a soybean or barley cover crop. A smaller but still significant increase of 15-20% was seen when grown as a harvested crop then incorporated, and also an increase in yield by 10-15% when grown only as a cover crop (Figure **5A**). However, it is also notable that the other crops also showed similar trends, with best results observed as a green manure crop, but significant improvements still apparent when used as a harvested then incorporated crop. This demonstrates the importance of incorporating organic matter of the residues, whether or not it is specifically a disease-suppressive crop or not.

A similar relationship was observed regarding the reduction of soil-borne disease, here represented by the severity of black scurf (Figure **5B**). The Mustard blend grown as green manure resulted in the lowest tuber disease

observed, reducing the severity of black scurf by 50% relative to a barley cover crop, and when grown for harvest and incorporated or as a cover crop, still reduced scurf by >30%, thus demonstrating the efficacy of the mustard blend in reducing soil-borne disease regardless of management practice. All other crops also reduced disease by 28-36% when grown as green manure, but sudangrass, rapeseed, and soybean also reduced disease by a lesser amount (20-32%) when grown as a harvested crop and then incorporated, and with sudangrass still providing some disease reduction even when grown as a cover crop without incorporation (Figure **5B**).
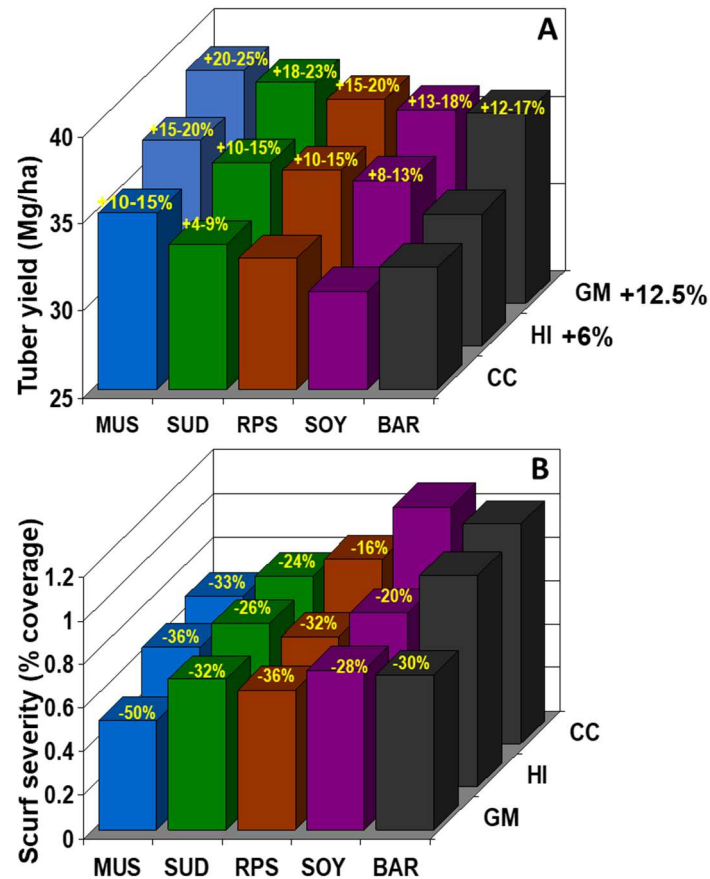

Figure 5: Combined effects of rotation crop management practice (representing different levels of residue incorporation) and rotation crop type on A) potato tuber yield and B) severity of black scurf tuber disease on the subsequent potato crop averaged over two potato cropping seasons (Adapted from Larkin and Halloran, 2014 [108]). Management practices: GM=green manure (all biomass incorporated green), HI=harvested crop (aboveground biomass removed) remaining stubble incorporate, CC=cover crop only, not incorporated. Rotation crops: MUS=Caliente Mustard Blend, SUD=Sudangrass, RPS='Dwarf Essex' rapeseed, SOY=soybean, BAR=barley/clover. Values topping bars indicate the percent change relative to SOY or BAR managed as a cover crop (CC) where differences were significant.

5. Integrated Cropping Systems for Disease Reduction

For best results on soil health and disease management, these practices should be incorporated into integrated cropping systems employing multiple approaches [10,109]. In our long-term cropping system trials in Maine, established in 2004, various soil and crop health management practices were used to develop cropping systems focused on management goals of soil conservation, soil improvement, and disease suppression [47,110,111]. All three systems were based on a 3-yr rotation rather than the standard 2-yr rotation, which was the typical rotation used by growers in the Northeast. The soil conserving (SC) system thus utilized this longer rotation (3 vs. 2-yr), reduced tillage (no-tillage in non-potato years, reduced tillage in potato year), and reduced erosion (straw mulch following potato harvest). The soil-improving (SI) system started with the same soil conserving rotation plus the addition of yearly compost amendments (composted dairy manure). The disease suppressive (DS) system utilized biofumigant green manures, cover crops, and crop diversity (different fall cover crops each

year). These systems were compared with a standard rotation (2-yr barley/red clover-potato) (SQ) and a continuous potato (non-rotation) (PP) control over several years (Table **1**).

Table 1:   Names, descriptions, and features of the cropping systems used to address specific management goals in long-term cropping systems trials in Maine (2004-2018).

Cropping System Parameters				
Name	**ID**	**Length**	**Original Rotation (2004-2012)**	**Modified Rotation (2013-2018) – (Comments)**
Status Quo	SQ	2-yr	Barley (Red clover) – Potato	No change - Typical rotation (Control)
Soil Conserving	SC	3-yr	Barley (Timothy) – Timothy (Limited tillage, straw mulch cover)	Barley (Ryegrass) – Canola/winter rye cover
Soil Improving	SI	3-yr	SC plus compost amendment	Barley (Ryegrass) – Canola (History of compost)
Disease Suppressive	DS	3-yr	Mustard GM/Rapeseed cover – Sudangrass GM/Rye cover	Barley (Ryegrass) – Mustard GM/rapeseed cover (Disease-suppressive green manure and cover crop)
Continuous Potato	PP	1-yr	Potato - Potato	No change - Non-rotation control

In the initial phase of the project (first eight years) [80,110,111], in which the potential for changes due to system differences was maximized and was conducted under both irrigated and non-irrigated conditions, all rotations increased tuber yield relative to the non-rotation control under both irrigated and non-irrigated conditions. When not irrigated, SI resulted in the highest yields of all systems, averaging 30% higher than SQ and 42% higher than PP, and DS also increased yield relative to the remaining systems (13-20% higher) (Figure **6A**). When irrigated, all systems (except SI) showed improved tuber yield (by ~25%), and DS system resulted in the overall highest tuber yields, averaging 20% higher than SQ. Under irrigated conditions, DS increased yield by 42% and 53% over non-irrigated SQ and PP, respectively. Regarding soil-borne tuber diseases, all rotations reduced the severity of tuber diseases (black scurf and common scab) relative to no rotation, and DS reduced the severity of black scurf more than all other systems under both irrigated and non-irrigated conditions, maintaining low disease levels throughout (Figure **6B**). Each cropping system also resulted in distinctly different soil microbial community characteristics, as represented by soil fatty acid methyl ester (FAME) profiles, indicating the effects of management practices and cropping systems on soil microbial communities [47,110].

After several years of observation, these systems were modified to be a more practical and better fit with grower needs and practices while still keeping the management concepts intact [112]. Thus, a cash crop of canola was added to SC and SI in place of the second full year of forage grass, the yearly compost amendments were stopped in SI (relying on the previous history of compost amendments), and the use of biofumigant green manure was reduced from 2 years to 1 year following a barley crop in the DS system. Details are indicated in Table **1**. Although these trials are ongoing, results from the period 2015-2018 showed that the SI system improved soil properties relative to all other systems and has maintained higher tuber yields (by 26%) and higher microbial activity (by 44%) relative to the standard SQ system. The DS system also maintained improved yield (by 16%) and increased microbial activity (by 23%) relative to SQ, as well as reducing soil-borne diseases (black scurf and common scab) by 10-30% [94]. Soil microbial community characteristics, as represented by fatty acid methyl ester (FAME) profiles and preliminary molecular analyses of the soil microbiome, also showed distinct differences among the cropping systems [113]. We are continuing to evaluate soil properties and soil microbiomes for each system to understand better the effects and differences among cropping systems and their potential relationship to disease management and productivity.

In other recent studies and analyses evaluating the incorporation of various crop rotations, cover crops, and other soil health management practices into potato cropping systems in various potato-growing regions, comparable trends have been observed. In eastern Canada, the use of cover crops and manure increased microbial activity and potato yields, provided better nutrient utilization, and reduced disease [20,23]. In Australia, the close relationship between soil health and productivity has been documented [114], and in New Zealand, improvements in soil health based on cropping history were shown to be associated with improved yield [115].
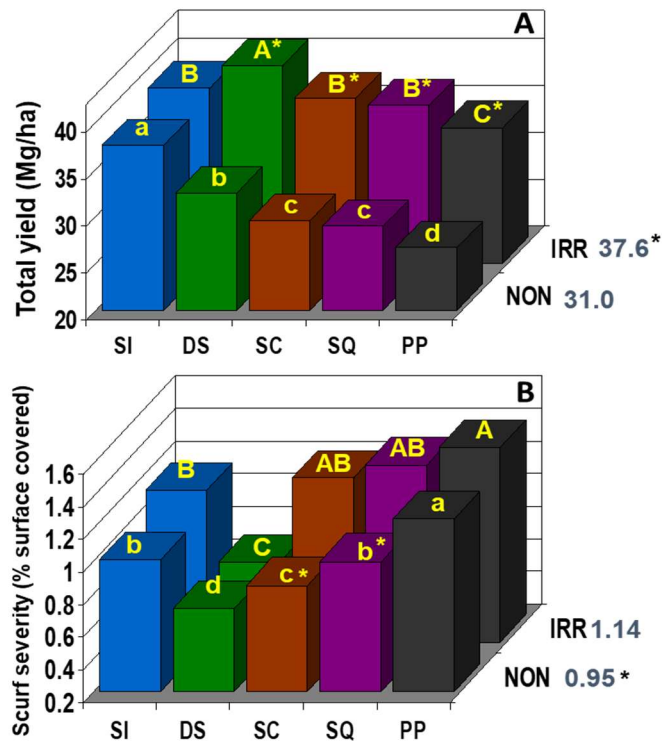
Figure 6: Effect of different cropping system management strategies with and without irrigation on A) potato tuber yield and B) severity of black scurf tuber disease averaged over five potato cropping seasons in long-term cropping system trials in Maine (Adapted from Larkin et al. 2017, 2021 [110,111]). Cropping systems: SI=Soil improving system (3-yr rotation, with compost amendments) system, SC=Soil conserving system (3-yr, reduced tillage, mulch), DS=Disease-suppressive system (3-yr, biofumigant green manures, crop diversity), SQ=Status quo (standard 2-yr rotation control, barley-potato), PP=continuous potato non-rotation control). IRR=Irrigated, NON=Not irrigated (rainfed). Bars topped by the same letter within each irrigation regime are not significantly different based on Fisher's protected LSD test (P=0.05). Bars (or values) with an asterisk (*) represent a significant reduction relative to the corresponding IRR bar or value.

6. Conclusions

In conclusion, incorporating management practices that promote soil health, such as the use of crop rotations, cover crops and green manures, organic amendments, and conservation tillage, into cropping systems, and in these examples, potato cropping systems, can improve soil physical, chemical, and biological properties, resulting in improved nutrition, enhanced yield, and disease suppression. Disease-suppressive rotation crops can also be effectively incorporated into potato cropping systems to provide improved management of soil-borne pathogens and other soil health benefits. In general, rotation crops grown as green manures were more effective than when grown as cover crops for their effects on tuber yield and disease, but positive effects on yield and disease reduction (albeit reduced) were still observed when grown as a harvested crop and then remaining residues incorporated. The importance of crop rotations and soil health management practices in productive potato cropping systems has been documented around the world [12,20,23,110,111,114,115]. The use of disease-suppressive crops and other soil health management practices can substantially reduce soil-borne disease problems, but cannot completely eliminate them, may take time to develop, and should be used in conjunction with other approaches to achieve sustainable disease management. Overall, it has been demonstrated that soil health management practices can be effectively incorporated into viable cropping systems that can improve soil properties and crop productivity and may enhance longer-term agricultural sustainability and viability.

Acknowledgments

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