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Long-Term Effects of Compost Amendments and Brassica Green Manures in Potato Cropping Systems on Soil and Crop Health and Productivity †

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Abstract: Beneficial soil and crop management practices, such as longer rotations, cover crops and green manures, organic amendments, and reduced tillage, may improve soil and crop health and productivity when incorporated into cropping systems. Long-term trials are needed to assess the full impacts and effects of these systems. In field trials originally established in 2004, three different 3-yr potato cropping systems focused on management goals of soil conservation (SC), soil improvement (SI), and disease suppression (DS) were evaluated and compared to a standard 2-yr rotation (SQ) and a nonrotation control (PP). After 12–15 years and results compiled over a four-year period (2015–2018), the SI system (with history of compost amendments) increased total and marketable tuber yields relative to all other systems, with yields averaging 26 to 36% higher than the standard SQ system and 36 to 59% greater than PP. SI also improved soil properties such as organic matter and soil water content, nutritional characteristics, and microbial activity compared to the other systems. The SI system continued to provide these improvements several years after compost amendments ended, indicating the long-term benefits. The DS system, which included a disease-suppressive green manure rotation crop and fall cover crops, also improved yield (by 16–20%), had higher organic matter content (by 12%), and increased microbial activity (by 22%) relative to SQ, as well as reducing the soilborne tuber diseases black scurf and common scab by 10–30%. The nonrotation PP system resulted in the notable degradation of soil properties and yield over time. These results demonstrate that soil health management practices can be effectively incorporated into viable potato cropping systems to improve soil properties and crop health, and may enhance long-term sustainability.

Keywords: black scurf; common scab; cover crops; disease suppression; soilborne disease; soil health; tuber yield

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1. Introduction

Potato (*Solanum tuberosum* L.) is the third most important food crop in the world [1] and the top agricultural commodity for the state of Maine [2]. Maintaining soil health is critical for agricultural sustainability and productivity but may be readily degraded by intensive production practices, resulting in losses in resilience, productivity, sustainability, economic viability, and environmental quality [3,4]. More specifically, intensive agricultural production disrupts soil structure, accelerates surface runoff, erosion, and the loss of organic matter and soil fertility, disrupts water and nutrient cycling, and has a major impact on soil biodiversity [4]. Potato production in the northeast US and some other potato growing regions has generally been characterized by short (2-yr) rotations, extensive tillage, minimal crop residue return, and minimal crop diversity, and has been shown to be detrimental to soil health and crop productivity over time [5–7], as well as leading to increases in losses due to soilborne diseases such as black scurf (caused by *Rhizoctonia solani*), common scab (caused by *Streptomyces scabies*), and Verticillium wilt (caused by *Verticillium dahliae*) [8,9]. Improved cropping systems are needed to enhance sustainability and productivity.

Several agricultural practices have been shown to help improve soil health and crop yield and reduce soilborne diseases, including increasing rotation length from 2 years to 3 or more years between potato crops [9–12], the addition of cover crops and green manures [13,14], amendments of compost or animal manure [15–18], and reduced tillage [10]. The incorporation of such soil and crop management practices into improved potato cropping systems may help enhance the productivity and sustainability of potato production systems. Most previous research, however, has focused primarily on the effects of individual practices and not necessarily on the combined effects of multiple different practices in integrated cropping systems for the assessment of total system effects on productivity, disease, and soil properties. The need for and importance of integrated management practices as well as long-term studies to fully assess these cropping systems for sustainable potato production have been emphasized in recent reviews [7,19,20].

In this research, which builds upon our previous work with improving potato cropping systems [8,21–27]), we assessed the longer-term effects of cropping systems incorporating multiple soil health management practices on soil properties, potato yield, and soilborne diseases. The potato cropping system field trials were originally established in 2004, with the development of three specific cropping systems addressing the crop and soil management goals of soil conservation, soil improvement, and disease suppression, and these were compared to a standard rotation and a nonrotation control [24]. The original trial was established to determine what factors were most limiting to potato production in Northeastern U.S., and how those limitations could be addressed through cropping systems. After monitoring those systems over the first several years of the project and characterizing their effects on soilborne potato diseases and soil microbiology [24,25,28,29], soil health (represented by various soil physical, chemical, and biological properties) [27,30], and crop growth and productivity [26], modifications were made to the systems in 2013 (as outlined below in Section 2) in order for the cropping systems to be more economically feasible and a better fit within current production practices for potato growers while still maintaining the same overall system approaches and goals. Thus, the objectives of the present research were to assess the more long-term effects (after 12–15 years) of these overall systems on yield, soilborne diseases, and soil properties, as well as to assess the relative success of the modified systems in maintaining and achieving the management goals of the original systems.

2. Materials and Methods

2.1. Cropping Systems

Cropping system consisted of five different systems designed to address specific management goals of soil conservation (SC), soil improvement (SI), and disease suppression (DS), as well as a system representing a typical standard rotation currently used in the Northeast US (SQ), and a nonrotation control of continuous potato (*Solanum tuberosum* L.) (PP). The trial was originally established in 2004 and monitored for several years. An overview of the cropping systems and their features is provided in Table 1. The original systems and their effects have been fully described and documented previously [24]. The original systems were designed to provide the maximum impact of the management practices and were not necessarily the most practical or economically feasible. Thus, in 2013, the systems were modified to be more practical for the grower and better fit within current production practices, while still maintaining the same relative system concepts and practices. Briefly, the modified systems consisted of a standard or 'status quo' rotation (SQ) with a 2-yr rotation of barley (*Hordeum vulgare* L.) underseeded with red clover (*Trifolium pretense* L.) as a cover crop, followed by potato the following year, with regular spring and fall tillage each year (no change from previous system). The soil-conserving system (SC) consisted of a 3-yr rotation of barley underseeded with ryegrass (as a cover crop), followed by canola as a cash crop, and then followed by potato in the third year. The soil-improving system (SI) consisted of the same basic rotation as SC (3-yr, barley/ryegrass–canola–potato) but with a previous history of compost amendments (composted dairy manure added at 45 Mg/ha/yr for 7 years, 2004–2010). However, no additional compost amendments had been made since 2010. The disease-suppressive system (DS) was designed to make use of multiple strategies for suppressing soilborne diseases, and included the use of disease-suppressive rotation crops, a longer rotation period, crop diversity, green manures, and fall cover crops. The DS system consisted of a 3-yr rotation with barley underseeded with ryegrass in the first year, followed by the disease-suppressive *Brassica juncea* L. 'Caliente 199' mustard blend grown as a green manure, followed by a fall cover crop of rapeseed (*Brassica napus* L. 'Dwarf Essex') in the second year, with potato in the third year. For this study, green manure refers to a crop whose full biomass was incorporated into the soil while fresh and green, whereas cover crop refers to a crop that is left in the field to overwinter unplowed and uncut. Continuous potato (PP) was the nonrotation control consisting of a potato crop planted in the same plots each year (spring and fall tillage). All systems were monitored under rainfed (not irrigated) conditions, as this is consistent with the majority of commercial potato production in Maine and the Northeastern US.

Table 1. Names, descriptions, and features of the cropping systems used to address specific management goals in these studies. GM = green manure crop.

Cropping System Parameters				
Name	**Designation**	**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 (Addition of cash crop)
Soil Improving	SI	3-yr	SC plus compost amendment	Barley/Ryegrass—Canola/winter rye (History of compost)
Disease Suppressive	DS	3-yr	Mustard GM/Rapeseed cover—Sudan grass 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—nonrotation control

2.2. Field Set-Up and Management

Research plots were located at the USDA-ARS New England Plant, Soil and Water Laboratory Field Experimental Site in Presque Isle, ME (46°38′56.4″ N, 68°00′28.5″ W, 142 m above sea level), and trial was conducted as a randomized complete block design with 5 replicate blocks. Soil type was a Caribou sandy loam (fine-loamy, isotic, frigid Typic Haplorthods). Each rotation phase or entry point (representing each possible rotation crop for all years) was included in each block, so that each full rotation was represented each year (SQ, 2 entry points; SC, SI, and DS, 3 entry points; and PP, 1 entry point), resulting in 12 treatment plots (3.7 × 15.1 m each) per block. Thus, each year, five of the 12 plots in each block were planted to potato, corresponding to their appropriate place in the rotation. A diagram showing the rotation and plot arrangement for two of the five replicate blocks is depicted in Figure 1. Data were only collected on the plots planted to potato each year, representing the results on the potato crop following the full rotation period. For potato planting, cut seed pieces of potato variety 'Russet Burbank' were planted in furrows in each plot (four rows, 0.9 m centers, with a 35 cm spacing between plants). Russet Burbank was chosen for use because it is the predominant variety grown by a majority of potato growers in this region. Potato plots were fertilized with the equivalent of 224 kg ha^{-1} N and 249 kg ha^{-1} P_2O_5 and K_2O. All potato plots were also sprayed with a pre-emergence herbicide (metribuzin at the rate of 1.0 kg a.i. ha^{-1}) within 2 weeks after planting. In-season cultivation included one or two shallow passes with a cultivator, and one pass with a hiller. Potato plots were also sprayed regularly throughout the growing season with alternating applications of mancozeb and chlorothalonil at recommended rates for the control of late blight. All other crops were managed using recommended production practices for that crop. Potato crop assessments reported here cover the period from 2015 to 2018, following the full 3-year cycle of modified rotations begun in 2013, constituting data from four consecutive cropping years.

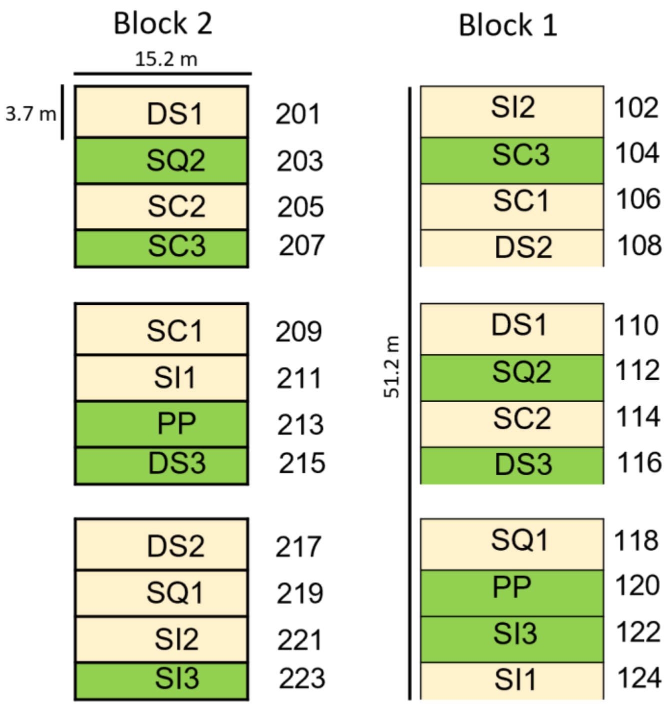

Figure 1. Diagrammatic representation of plot layout for two of the five replicate field blocks showing the cropping system (SQ—standard rotation, SC—soil conserving, SI—soil improving, DS—disease suppressive, and PP—nonrotation control) followed by the rotation phase (1, 2, or 3—first, second, or third year of rotation). Potato is last crop in the rotation sequence and plots grown to potato in 2015 are shown in green. In subsequent years, different plots are grown to potato as determined by the cropping system phase. The number to the right of each plot indicates the plot number for identification purposes.

Site environmental conditions, including air and soil temperature, relative humidity, and rainfall were monitored throughout each growing season using a Watchdog 2000 Series weather station (Spectrum Technologies, Aurora, IL, USA) outfitted with temperature probes and a tipping bucket rain gauge. Data were recorded every hour and converted to daily minimum, maximum, and average values as well as total daily rainfall. For ease of presentation, temperature and rainfall data were summarized as average monthly values for each year of the study (Table 2).

Table 2. Average daily temperature and total monthly rainfall for the months of May through September at the Presque Isle research site for 2015 to 2018 compared with long-term (30-year) average conditions.

	Average Daily Temperature (°C)					Total Monthly Rainfall (cm)				
	2015	**2016**	**2017**	**2018**	**Long-Term Avg**	**2015**	**2016**	**2017**	**2018**	**Long-Term Avg**
May	14.2	12.8	11.5	12.6	11.4	7.5	6.8	11.9	4.9	8.7
June	15.0	16.5	16.5	15.8	16.4	11.4	8.7	8.9	7.6	8.6
July	18.3	19.6	19.2	22.5	19.0	6.5	15.9	4.7	6.6	9.4
August	20.3	19.7	18.1	20.8	18.2	8.9	12.9	4.4	8.3	10.0
September	17.1	15.4	16.8	14.7	13.2	10.4	4.6	12.9	5.6	8.7
Season avg	17.0	16.8	16.4	17.3	15.6	44.8	48.9	42.8	33.0	45.4

2.3. Tuber Yield and Size

In October of each year, potatoes were harvested from the full length of the center two rows from each potato plot. Total weight of the harvested tubers was used to determine total yield on a Mg ha^{-1} basis. A subset of the harvested tubers, amounting to a total of 20–25 kg per plot and taken from multiple randomly selected plot sections, were washed, graded and sized into 4 categories from small to extra-large (small, <114 g; medium, 114–227 g; large, 228–342 g; and extra-large >342 g). Marketable yield was calculated as the proportion of the total weight of tubers of a size greater than 114 g each.

2.4. Soil Properties

Soil samples were collected from all plots within the same day each spring (just prior to field preparation) for soil property assays. Five soil cores (7.5 × 15 cm) collected from throughout each plot were combined into one composite sample per plot, sieved through a 2-mm screen, and used for all subsequent analyses. Samples were divided into those used for physical and chemical analyses, which were air-dried and stored until processed, and those used for biological assays, which were stored in plastic bags at field moisture at 8 °C and processed within one week. Soil water content was determined as gravimetric water content at the time of sampling from a 10 g subsample of the composite soil sample from each plot.

All soil chemical composition analyses were based on the composite soil sample taken per plot in the spring (prior to field preparation and planting) of each year. Extractable soil mineral N, as nitrate (NO_3^-) and ammonium (NH_4^+) was determined using standard (cold water bath) KCl extractions according to procedures of Gianello and Bremner [31]. Soil concentrations of Ca, K, Mg, P, Al, Fe, Mn, Zn, S, Cu, and Na were estimated using Modified Morgan extraction procedures, according to Helmke and Sparks [32], and analyzed using inductively coupled plasma optical emission spectroscopy (ICP-OES) by the University of Maine Analytical Lab (Orono, ME, USA). Values were expressed as mg kg^1 soil.

Soil microbiological properties were assessed by soil respiration and substrate utilization assays as indicators of microbial biomass and activity. Soil respiration was measured using the Solvita CO_2 burst assay [33,34]. The capability of soil microbial communities to utilize a variety of sole carbon sources was assessed using BIOLOG GN2 plates (BIOLOG Inc., Hayward, CA, USA) by a procedure previously described by Larkin [35]. Average well color development (AWCD) was used as an indicator of microbial activity. In addition, substrate utilization data were analyzed for substrate richness (the number of substrates utilized) and substrate diversity (using Shannon's diversity index) [35]. In addition, populations of culturable fungi and bacteria were quantified by dilution plating assays on semi-selective media, potato dextrose agar with 50 mg chlortetracycline, and 1 mL L^{-1} tergitol added for fungi and 0.1% tryptic soy agar for bacteria following previously published methodology [35]. All biological assays used three soil subsamples from each composite soil sample per plot.

2.5. Disease Assessments

Potato plants were monitored in the field throughout the growing season for signs and symptoms of soilborne diseases, including Rhizoctonia stem and stolon canker, white mold, and Verticillium wilt. A subset of the harvested tubers, consisting of at least 40 tubers of marketable weight, was rated for incidence and severity of soilborne diseases of tubers, including black scurf, common scab, powdery scab, and silver scurf. Disease severity for all tuber diseases was determined as the approximate percent surface coverage of the visible symptoms on each tuber.

2.6. Statistical Analyses

All data analyses were conducted using the Statistical Analysis Systems ver. 9.4 (SAS Institute, Cary, NC, USA). Data from each potato crop year were analyzed using standard analysis of variance (ANOVA) for a randomized complete block design. Data from all years were also combined and analyzed (with year and interactions as additional factors) using a linear mixed models (PROC MIXED in SAS) analysis with year as a random effect, in order to evaluate cumulative and multiyear effects of the cropping systems. Mean separation was accomplished with Fisher's protected LSD test for single year evaluations and pairwise t-test comparisons of least square means (DIFF option in SAS) for multiple year evaluations. Correlation analyses were conducted (using Pearson's product-moment correlation coefficients) among yield, disease, and soil property parameters to determine parameters most closely associated with productivity. Principal components analysis (PCA) using the correlation matrix followed by multivariate analysis of variation (MANOVA) were conducted to summarize the overall variation related to soil properties among samples. Substrate utilization data were analyzed by analysis of covariance and adjusted least square means compared among systems for substrate richness and diversity analyses. AWCD was used as a covariate to account for the influence of AWCD on substrate utilization patterns [35]. Significance was evaluated at $p < 0.05$ for all tests.

3. Results

3.1. Tuber Yield

Overall, potato tuber yields were greatly affected by weather and environmental conditions that varied by year. Dry summer conditions in 2017 and 2018 (with rainfall deficits of up to 100 mm) resulted in lower than average yields, whereas abundant rainfall in 2016 resulted in above average yields, nearly double those observed in 2017. The soil-improving (SI) system, which had a previous history of compost amendments, resulted in the numerically highest total tuber yields, as well as significantly greater yields than the SQ and PP systems for all 4 years (2015–2018) studied, with increases ranging from 19–48% (Table 3). The disease-suppressive (DS) system also resulted in total yields significantly greater than SQ and PP in 2017 and 2018 (by 18–45%). The soil-conserving (SC) system showed significantly greater total yields than PP in 2015 and 2017, but was not significantly greater than SQ in any single year. Marketable yield (tubers > 114 g) followed similar trends, although DS, but not SI, had a significantly higher marketable yield than SQ and PP in 2018. The continuous potato (PP) nonrotation control consistently resulted in the lowest yields of all systems. With combined data over all four years, the 3-yr cropping systems significantly increased total yield over the SQ and PP systems and all cropping systems significantly increased marketable yield over PP, with DS and SC increasing total yield relative to SQ (by 9–16%) and DS also increasing marketable yield by 20% compared to SQ (Figure 2). However, SI produced significantly higher overall yields than all other systems, with increases in total and marketable yield averaging 36% and 59% higher than PP and 26% and 36% higher than SQ (Figure 2).

Table 3. Effect of different cropping systems on total tuber yield and marketable yield each year from 2015 to 2018.

System ^{y}	Total Tuber Yield (Mg/ha)				Marketable Yield (Mg/ha)			
	2015	**2016**	**2017**	**2018**	**2015**	**2016**	**2017**	**2018**
SI	30.1 a ^{z}	49.7 a	25.7 a	27.9 a	21.2 a	38.9 a	16.7 a	17.2 ab
DS	27.1 ab	42.9 ab	25.4 a	26.5 a	20.1 a	30.9 b	13.8 ab	17.7 a
SC	27.9 ab	40.4 b	22.4 ab	24.9 ab	18.9 a	29.0 bc	11.9 b	16.0 abc
SQ	25.1 bc	35.7 b	21.6 b	23.0 b	17.6 ab	26.0 bc	11.7 b	13.4 c
PP	21.9 c	36.1 b	17.4 c	22.4 b	14.5 b	23.7 c	5.9 c	14.2 bc
LSD ($p = 0.05$)	4.4	6.8	3.5	3.1	4.3	7.2	3.5	3.5

^{y} SI = soil improving, SC = soil conserving, DS = disease suppressive, SQ = status quo, PP = continuous potato systems. ^{z} Values within columns followed by the same letter are not significantly different from each other based on ANOVA and Fisher's protected LSD test ($p < 0.05$).

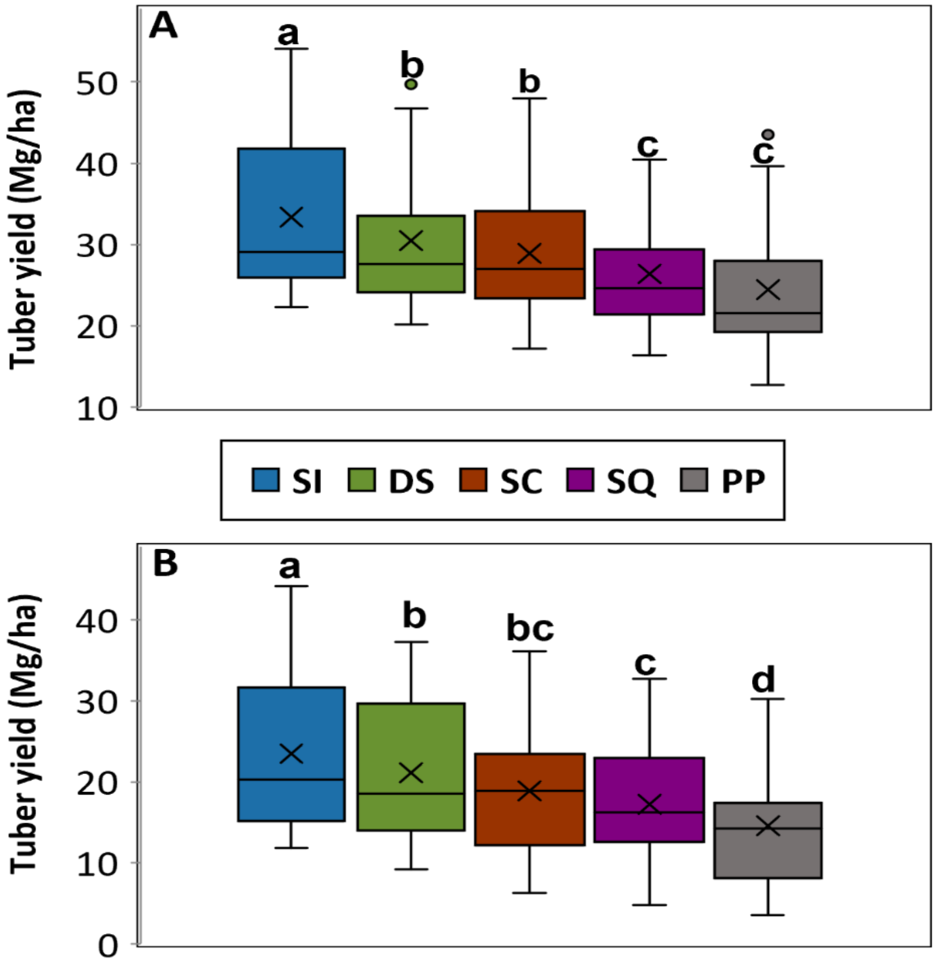

Figure 2. Effects of cropping system (SQ—standard rotation, SC—soil conserving, SI—soil improving, DS—disease suppressive, and PP—nonrotation control) on (**A**) total and (**B**) marketable tuber yield over a 4-year period (2015–2018). Bars topped by the same letter are not significantly different from each other based on pairwise *t*-tests ($p < 0.05$). Data points outside of the depicted range indicate outliers.

SI and DS averaged the highest percentage of tubers in the large (228–342 g) and extra-large (>342 g) size classes among the cropping systems, accounting for 31% and 29% of all tubers, respectively, and significantly greater than for PP (19%) (Figure 3). The largest individual size class for the SI, DS, SC, and SQ systems was the medium size class (115–227 g), accounting for ~37% of the total, whereas the largest size class for the PP system was small (<114 g), below marketable tuber size, comprising 44% of the total, respectively. Thus, PP had the lowest overall percentage of marketable tubers (comprising all size classes greater than small), at 56% for PP vs. 63% to 68% for all other systems (Figure 3).

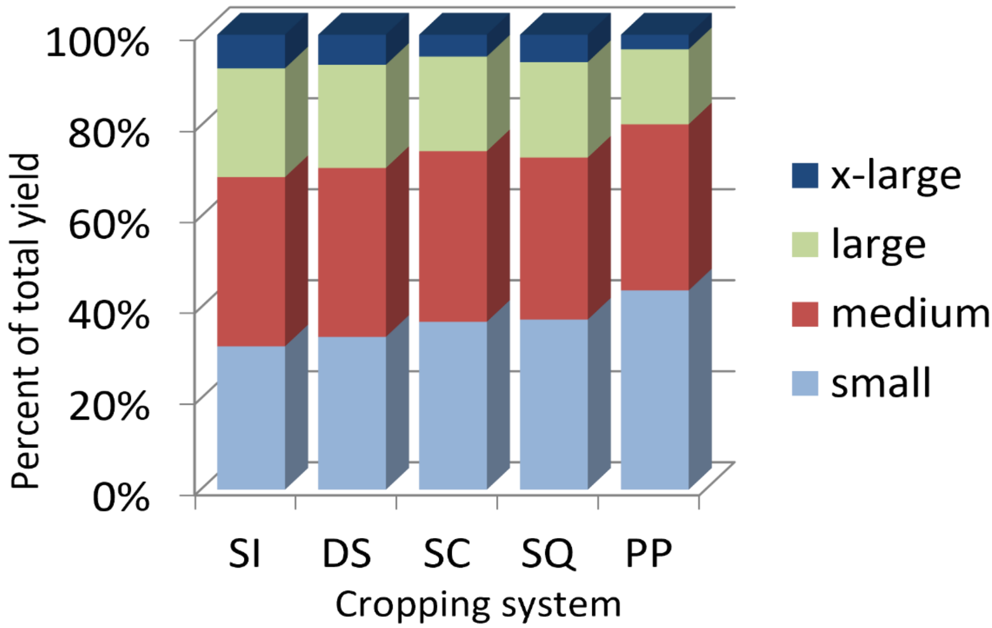

Figure 3. Effect of cropping system (SQ—standard rotation, SC—soil conserving, SI—soil improving, DS—disease suppressive, and PP—nonrotation control) on tuber size class distribution from combined data over four cropping seasons (2015–2018).

3.2. Disease Assessments

Black scurf and common scab were the primary tuber diseases observed throughout the study. The incidence and severity of black scurf on tubers varied somewhat from year to year, but the DS system consistently reduced black scurf, and was the only system to significantly reduce both the incidence and severity of black scurf relative to PP in all four years, with reductions ranging from 15% to 85% (Table 4). SI and SC systems reduced the incidence and severity compared to PP in 3 of the 4 years, and both DS and SI reduced the incidence and severity relative to SQ in 2 of the 4 years (Table 4). With combined data over all four years, all cropping systems reduced the severity of black scurf relative to PP (by 11–29%), with DS reducing disease relative to all other systems but SI, and SI reducing disease relative to SQ and PP (Figure 4a).

Table 4. Effect of different cropping systems on development of black scurf (caused by *Rhizoctonia solani*) on potato tubers over four field seasons (2015–2018).

	Black Scurf Disease							
	Incidence (% Infected Tubers)				Severity (% Surface Coverage)			
System [y]	2015	2016	2017	2018	2015	2016	2017	2018
SI	14.0 b [z]	20.7 ab	4.0 b	4.0 b	0.95 b	1.15 ab	0.81 bc	0.86 c
DS	14.6 b	10.0 c	4.7 b	6.0 b	0.95 b	0.98 c	0.71 c	0.85 c
SC	30.7 a	10.0 c	8.7 b	9.3 b	1.23 a	1.01 c	0.85 b	0.96 b
SQ	32.7 a	13.3 bc	23.3 a	9.3 b	1.21 a	1.04 bc	1.15 a	0.96 b
PP	24.7 a	22.0 a	22.7 a	41.3 a	1.11 a	1.19 a	1.19 a	1.41 a
LSD (p = 0.05)	10.2	7.4	8.4	7.1	0.13	0.12	0.13	0.10

[y] SI = soil improving, SC = soil conserving, DS = disease suppressive, SQ = status quo, PP = continuous potato systems. [z] Values within columns followed by the same letter are not significantly different from each other based on ANOVA and Fisher's protected LSD test ($p < 0.05$).

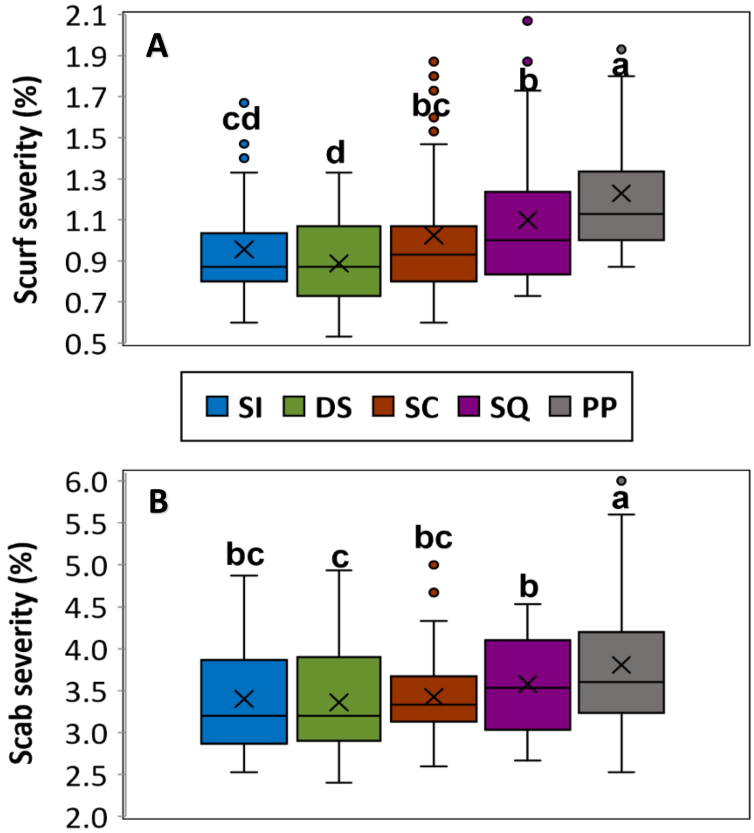

Figure 4. Effects of cropping system (SQ—standard rotation, SC—soil conserving, SI—soil improving, DS—disease suppressive, and PP—nonrotation control) on the severity (represented by percent surface coverage) of soilborne tuber diseases (**A**) black scurf and (**B**) common scab over four cropping seasons (2015–2018). Bars topped by the same letter are not significantly different from each other based on pairwise *t*-tests ($p < 0.05$). Data points outside of the depicted range indicate outliers.

The incidence and severity of common scab also varied from year to year, and DS significantly reduced both relative to PP in all four years, with reductions of 12–48%, and relative to SQ in two of the four years (Table 5). SI also reduced incidence and severity compared to PP in three years. With combined data over all four years, all cropping systems reduced scab severity compared to PP, and DS also significantly reduced scab severity compared to SQ (Figure 4b).

Table 5. Effect of different cropping systems on development of common scab (caused by *Streptomyces scabies*) on potato tubers over four field seasons (2015–2018).

	Common Scab Disease							
	Incidence (% Infected Tubers)				Severity (% Surface Coverage)			
System [y]	2015	2016	2017	2018	2015	2016	2017	2018
SI	38.7 b [z]	71.3 b	27.3 ab	27.3 bc	3.48 b	4.31 b	3.12 ab	3.10 bc
DS	46.7 b	72.7 b	20.0 b	22.0 c	3.55 b	4.12 b	2.93 c	2.95 c
SC	48.0 ab	68.0 ab	22.0 b	35.3 ab	3.70 ab	4.20 b	3.05 bc	3.24 b
SQ	51.3 ab	70.0 b	36.0 a	29.3 bc	3.73 ab	4.21 b	3.28 a	3.20 b
PP	61.3 a	84.7 a	34.0 a	42.0 a	4.02 a	4.93 a	3.18 ab	3.41 a
LSD ($p = 0.05$)	14.0	9.9	9.2	9.0	0.42	0.24	0.16	0.16

[y] SI = soil improving, SC = soil conserving, DS = disease suppressive, SQ = status quo, PP = continuous potato systems. [z] Values within columns followed by the same letter are not significantly different from each other based on ANOVA and Fisher's protected LSD test ($p < 0.05$).

3.3. Soil Properties

Soil physical and chemical properties were also affected by the different cropping systems. Differences were generally consistent from year to year, so results are shown as averages over a 3-year period (2016–2018). Soil pH was lower in PP than in the 3-yr systems, indicating a decline from initial levels (~6.0) (Table 6). Soil organic matter (OM) and gravimetric soil water content (sampled in spring) were significantly higher in SI than all other systems throughout the study, with SI OM content averaging 43–60% higher than in SQ and PP. OM content for DS was also significantly greater than for SQ and PP, by 4–24% (Table 6). OM content for PP was lower than all other systems, having declined from initial values by about 0.5%.

Table 6. Effect of different cropping systems on soil physical properties soil pH, soil water content, and organic matter content (OM) measured in the spring of each year over three cropping seasons (2016–2018).

	Soil Physical Properties ^{x}		
System ^{y}	pH	Soil Water (%)	OM (%)
SI	5.99 a ^{z}	20.6 a	5.65 a
DS	5.96 a	19.1 b	4.40 b
SC	5.95 a	18.2 bc	4.08 bc
SQ	5.88 ab	18.3 bc	3.94 cd
PP	5.82 b	17.9 c	3.54 d
LSD (p = 0.05)	0.11	1.1	0.42

^{x} Initial (2004, prior to implementation of cropping systems) average values were 5.90 for pH, 22.7% for soil water, and 3.9% for OM content, with no differences among cropping systems. ^{y} SI = soil improving, SC = soil conserving, DS = disease suppressive, SQ = status quo, PP = continuous potato systems. ^{z} Values within columns followed by the same letter are not significantly different from each other based on pairwise *t*-tests ($p < 0.05$).

Soil concentrations of macronutrient elements tended to be highest for SI than all other cropping systems for most compounds, including NO_3-N, NH_4-N, P, K, Ca, and Mg, as well as for cation exchange capacity (CEC) (Table 7). Concentrations were also lowest in PP for some nutrients, including significantly lower than SC and SQ for NO_3, lower than DS for Ca, and lower than DS and SC for Mg (Table 7). Soil concentrations of some micronutrient elements also varied among cropping systems, with higher levels observed in SI for manganese, boron, and zinc than all other systems, and higher levels in both SI and PP for sulfur than all other systems. In addition, SI recorded the lowest concentrations of the metals Al and Cu than all other systems, and DS and SC showed lower Na than some other systems, whereas Fe showed no significant differences among cropping systems (Table 8).

Soil biological properties were also affected by the cropping system. Microbial activity, represented by CO_2 respiration and overall substrate utilization (average well color absorbance, AWCD, in Biolog substrate utilization test) was higher in SI than all other cropping systems, representing an increase of 44% and 148% relative to SQ and PP for CO_2 (Table 9). On the other hand, the continuous potato (PP) system showed a significantly lower respiration and AWCD than all other cropping systems. PP also showed the lowest substrate richness (number of different substrates used) and substrate diversity than all other systems in substrate utilization assays, whereas SI showed higher richness than SC, and DS showed higher diversity than SQ (Table 9). Populations of culturable bacteria were also lowest in PP soil, followed by SC, whereas populations of culturable fungi were similar across most of the systems, but with SC showing lower overall fungal populations. Populations of the specific beneficial group of fungi representing *Trichoderma* spp. were lowest in PP, followed by SQ, whereas a particular group of *Penicillium* spp. that has been associated with potato production in these soils was much higher in PP soil than all other systems (Table 9).

Table 7. Effect of different cropping systems on soil chemical properties, including NO3-N, NH4-N, P, K, Ca, Mg, Mn concentrations, and cation exchange capacity (CEC) from combined data over three cropping seasons (2016–2018).

System ^{y}	Nutrient Concentrations (mg kg^{-1} Soil) ^{x}						meq 100 g^{-1} Soil
	NO_3	NH_4	P	K	Ca	Mg	CEC
SI	10.6 a ^{z}	4.0 a	20.2 a	308.5 a	1434 a	283.0 a	8.4 a
DS	5.7 b	3.1 bc	15.0 b	242.6 bc	1076 b	214.7 bc	7.1 b
SC	6.2 b	4.1 a	14.6 b	215.0 c	1014 bc	229.8 b	6.9 b
SQ	6.4 b	3.3 b	16.8 b	257.6 b	1019 bc	189.8 cd	7.0 b
PP	4.7 b	2.5 c	16.5 b	250.7 bc	906 c	164.5 d	6.7 b
LSD (p = 0.05)	1.6	0.66	2.6	34.8	141	32.1	0.5

^{x} Initial (2004, prior to implementation of cropping systems) average values (in mg kg^{-1} soil) were 8.6 and 8.9 for NO_3-N and NH_4-N, and 17.6, 142, 613, and 161, for P, K, Ca, and Mg, respectively, with no differences among cropping systems. Initial CEC value averaged 5.6 meq 100 g^{-1} soil. ^{y} SI = soil improving, SC = soil conserving, DS = disease suppressive, SQ = status quo, PP = continuous potato systems. ^{z} Values within columns followed by the same letter are not significantly different from each other based on pairwise *t*-tests (p < 0.05).

Table 8. Effect of different cropping systems on concentrations of micronutrient elements in soil, including Mn, Na, S, B, Fe, Al, Cu, and Zn from combined data over three cropping seasons (2016–2018).

System ^{y}	Nutrient Concentrations (mg kg^{-1} Soil)							
	Mn	Na	S	Fe	Al	Cu	B	Zn
SI	6.27 a ^{z}	10.0 ab	6.87 a	5.42 a	79.1 b	0.85 b	0.26 a	1.00 a
DS	5.43 b	9.8 b	5.20 b	5.08 a	95.1 a	1.13 a	0.18 b	0.61 bc
SC	5.21 b	9.3 b	5.13 b	5.27 a	99.4 a	1.24 a	0.18 b	0.47 c
SQ	5.65 b	10.7 ab	5.40 b	5.61 a	98.7 a	1.29 a	0.20 b	0.67 bc
PP	5.40 b	11.6 a	6.40 a	5.54 a	104.7 a	1.17 a	0.18 b	0.68 b
LSD (p = 0.05)	0.62	1.8	0.84	0.67	11.6	0.22	0.04	0.20

^{y} SI = soil improving, SC = soil conserving, DS = disease suppressive, SQ = status quo, PP = continuous potato systems. ^{z} Values within columns followed by the same letter are not significantly different from each other based on pairwise *t*-tests (p < 0.05).

Table 9. Effect of different cropping systems on selected soil biological properties, including microbial activity represented by CO_2 respiration and substrate utilization, and culturable populations of select microorganism groups from combined data over three cropping seasons (2016–2018).

System ^{y}	Respiration	Biolog (Substrate Utilization)			Culturable Populations (Dilution Plating)			
	CO_2 (ppm)	AWCD (absorbance)	Richness (#)	Diversity (Index)	Bacteria ($\times 10^6$)	Fungi ($\times 10^4$)	Tricho. ($\times 10^4$)	Penicil. ($\times 10^4$)
SI	141.1 a ^{z}	0.564 a	58.2 a	4.12 ab	58.5 a	38.5 a	1.80 ab	0.62 bc
DS	119.6 b	0.484 b	57.6 ab	4.13 a	55.4 a	36.1 a	1.78 ab	0.47 c
SC	103.6 c	0.515 b	57.1 b	4.11 ab	48.4 b	29.8 b	1.88 a	0.91 bc
SQ	97.7 c	0.499 b	57.3 ab	4.10 b	56.9 a	37.7 a	1.23 b	1.26 b
PP	56.8 d	0.438 c	53.8 c	4.03 c	37.1 c	38.9 a	0.58 c	6.13 a
LSD (p = 0.05)	15.9	0.034	1.0	0.03	5.6	4.6	0.55	0.64

^{y} SI = soil improving, SC = soil conserving, DS = disease suppressive, SQ = status quo, PP = continuous potato systems. ^{z} Values within columns followed by the same letter are not significantly different from each other based on pairwise *t*-tests (p < 0.05). Tricho. = *Trichoderma* spp. and Penicil. = *Penicillium* spp. associated with potato.

Principal components analysis of the measured crop and soil properties indicates the combined variability among samples related to cropping system effects, as well as showing which properties contributed most to that variability. Although properties varied somewhat by year, all cropping systems were significantly different from PP for overall combined properties, and SI also showed different characteristics from all other systems, with PP and SI at opposite ends of PC1 (higher values for SI, lower values for PP) (Figure 5A). The properties of the remaining systems were not significantly distinct from one another. Properties were most consistent from year to year for PP, with the other systems showing more yearly variation, and with 2017 showing higher PC1 values than the other two years for all systems. PC1 accounted for 29.6% of the total variability and PC3 accounted for 11.4% (PC2 accounted for 21.6% and was primarily associated with yearly differences and is not presented here). The parameters providing the greatest contribution to PC1 included OM, CO_2 respiration, Mg and Ca concentrations, and CEC, and the parameters contributing most to PC3 were black scurf incidence and severity, pH, and P concentration (Figure 5B).

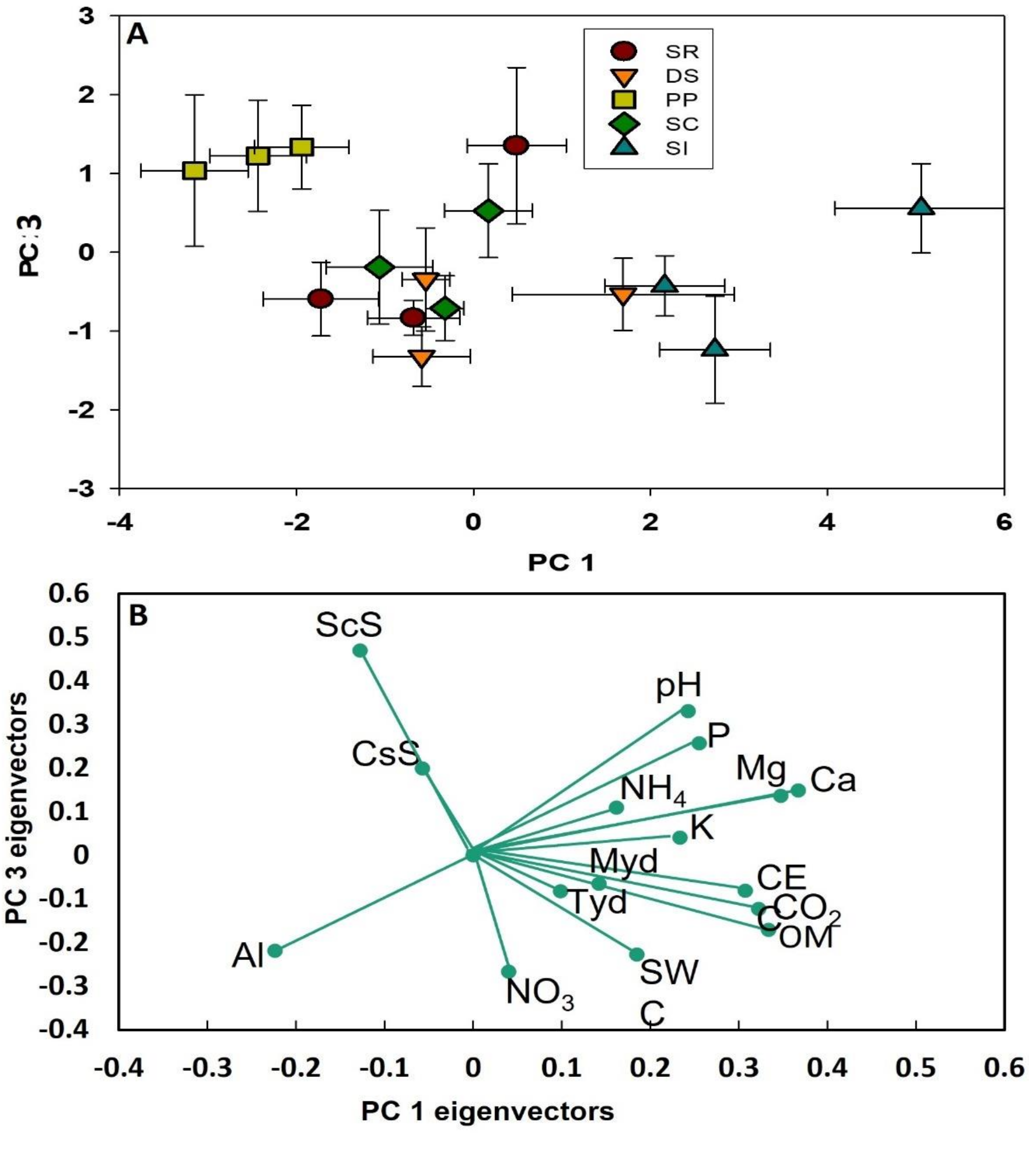

Figure 5. (**A**) Effects of cropping system (SQ—standard rotation, SC—soil conserving, SI—soil improving, DS—disease suppressive, and PP—nonrotation control) on crop and soil properties, as represented by principal components (PCs) 1 and 3 from principal components analysis assessed in each of three cropping years (2016–2018); and (**B**) PC eigenvectors for each soil property representing the loading factor contributing to the total variability for PCs 1 and 3 (Al, P, K, Mg, Ca, NO_3, NH_4 indicate respective soil nutrient concentrations, OM = organic matter content, CO_2 = CO_2 respiration, CEC = cation exchange capacity, SWC = soil water content, ScS = black scurf severity, CsS = common scab severity, Tyd = total tuber yield, Myd = marketable tuber yield).

Total and marketable yields were significantly correlated with a number of measured parameters in all three years monitored, including being highly correlated (p < 0.01) with OM content (r = 0.48–0.60), CO_2 respiration (r = 0.44–0.70), and soil moisture content (r = 0.35–0.78). Over all years, total and marketable yields were also correlated with the substrate utilization parameters AWCD, SR, and SD. Total and marketable yields were also correlated with soil Mg and Ca concentration in 2017, and total yield with Mg and Ca in 2016. In some years, yield was negatively correlated with disease development, as in 2017 with total yield negatively correlated with black scurf incidence and severity (p < 0.05, r = −0.45) and in 2018 with total yield negatively correlated with common scab incidence and severity (p < 0.05, r = −0.35 to −0.51).

4. Discussion

In this research, which is a continuation of the assessment of different potato cropping systems established in 2004 where multiple individual soil health management practices were combined into cropping systems with specific management goals of soil conservation, soil improvement, and disease suppression in relation to a standard rotation and no rotation, the longer-term effects on potato yield, disease development, and soil properties were evaluated over four full potato cropping seasons (2015–2018). In addition, modifications were made to some of the systems in 2013 to be more practical and to fit better into grower's practices while still maintaining the overall management goals. Combined data from all four seasons confirmed that the cropping system continued to significantly affect virtually all of the crop and soil characteristics measured, with the soil-improving (SI) system, which had a history of compost amendments, producing the greatest overall effects and improvements in various soil health and crop production parameters.

Overall, all crop rotations increased total and marketable tuber yields over no rotation (PP), and all of the 3-yr rotations increased total yield relative to the 2-yr standard rotation, but the SI system resulted in the highest tuber yield of all systems (both total and marketable), averaging 27 to 59% higher than SQ and PP systems over all years. The largest differences occurred in marketable yield in 2017 when the driest summer months resulted in especially low yields, and SI produced marketable yields that were 183% greater than in PP. Highly variable summer rainfall across the four years greatly affected potato yields, demonstrating the critical importance of soil water availability for potato yield [36,37], yet the SI system maintained higher yields throughout. Both SI and DS also resulted in the highest percentage of large and extra-large size-class tubers, and fewer small or under-sized tubers than PP. These SI effects on yield are a result of the many other changes observed due to this system, including higher organic matter and soil water content, higher microbial activity, and improved nutritional qualities. Recent research has emphasized that soil structure and water availability as affected by organic matter content and related properties are primary factors in yield and productivity [37–40].

Our previous reports on these systems also documented significant SI effects on a variety of other soil properties associated with soil health, including increased total and particulate organic matter C and N, active C, aggregate stability, microbial biomass C, and other soil microbial community characteristics, as well as lowered bulk density relative to the other cropping systems [24,25,27]. These effects indicate the important role of the compost amendments in improving soil properties and soil health attributes in these soils. In other research, compost amendments have been shown to provide similar increases in organic matter, water availability, and other soil quality parameters, as well as generally higher tuber yields [16,41–45]. Organic matter amendments improve soil structural stability primarily through increases in aggregate stability, and also improvements in bulk density, aeration, porosity, and water movement [46–49]. However, the current research has also shown that improvements due to compost amendments can have long-lasting effects, as compost amendments in this study were all applied between 2004 and 2010; thus, no compost was applied in the previous 5–8 years of the assessments made in the current study (2015–2018). Yet, OM content, yield, microbial activity, and other soil parameters were maintained at levels above those of the other cropping systems in the SI system. This indicates that once OM content is increased to a sufficient level, soil health benefits will continue to be realized provided OM remains elevated, and that higher OM levels can be maintained for extended periods without additional compost amendments. OM content did show a decline after amendments were ceased, but the inclusion of cover crops and other management practices in SI were sufficient to maintain OM at a level higher than other systems. These higher OM levels may be able to be maintained indefinitely with only occasional or periodic additional amendments rather than yearly or biannual additions, such as once every several years or so. Thus, the full effects of the SI system resulted not only from the previous compost amendments, but from the combination of multiple practices, including the longer rotation period and use of cover crops in addition to the organic amendments. Combinations of multiple soil improvement practices have also provided the best and most consistent results in other potato cropping systems research [15,50].

The SI system also resulted in lower incidence and severity of the soilborne tuber disease black scurf than the SQ and PP systems in multiple individual years, as well as when averaged over all years, but was only lower than PP for common scab. In earlier short-term assessments [24,25], SI did not significantly reduce any soilborne disease relative to SQ, only relative to PP. Thus, better suppression of black scurf developed over several years in SI, achieving results nearly comparable to DS (at least for black scurf). This indicates that biological properties developed over time to reduce disease severity, potentially due to changes in soil microbial characteristics, general suppression, or other biological mechanisms. Other research has indicated the effects of compost and organic matter amendments on soil microbiology and soil microbial communities [41,51], as well as significant effects on soilborne diseases [52], and organic amendments have been noted for their role in shaping soil microbial communities and the development of disease-suppressive soils [53,54]. However, some short-term studies have not shown significant effects on soilborne diseases or potato yield with various compost amendments [55,56]. In the current study, the reduction in soilborne diseases was an effect that was not apparent earlier, took time to develop, and thus demonstrates the need for such long-term assessments of cropping systems over time.

The DS system also resulted in overall higher yields than the SQ and PP systems (by 15 to 40%) and continued to result in lower soilborne disease, represented by reductions in the incidence and severity of black scurf and common scab. However, the DS system had relatively minor effects on various soil chemical and physical characteristics, with no significant differences from SQ for macro and minor-element concentrations, pH, or soil water content. DS did increase OM content and microbial activity (CO_2 respiration). These effects were presumably due to the beneficial effects of the added disease-suppressive Brassica green manure and cover crops and their impacts on soilborne pathogens and soil microbial community characteristics. In previous reports, DS also resulted in lower incidence and severity of multiple soilborne diseases, as well as significant effects on soil microbial community characteristics, but only minor effects on soil chemical and biological parameters [24,25]. Thus, in the current system, DS has maintained these disease reduction and soil microbial community properties through several more years of these cropping systems. In a meta-analysis of over 100 studies on the effects of green manures in many different cropping systems (most notably wheat, corn, and potato), Ma et al. [57] observed that green manures consistently increased soil organic matter content, microbial biomass, enzyme activity, and nutrient concentrations, as well as an overall 6% increase in potato yields. In another meta-analysis of hundreds of experiments utilizing biofumigation, Morris et al. [58] noted generally reduced pest abundances and disease incidence, as well as increased crop yield. In other potato studies in Maine and Canada, Brassica green manures have resulted in significant reductions in multiple soilborne diseases as well as improved yield [21,59,60].

Although the modifications made to the systems in 2013 reduced the DS green manures from multiple years to a single year per cropping cycle, soilborne diseases were still reduced relative to the other systems at comparable levels as previously observed in earlier years of the study [24,25]. Thus, a single year of a disease-suppressive Brassica green manure crop, along with additional disease-reducing strategies within a cropping system, appears to be adequate to maintain relatively low disease pressure from these soilborne diseases. Effects on and changes in the soil microbial communities are apparently very important factors for both the SI and DS systems, and although not explicitly addressed in the current study, full analyses of the composition and function of the soil microbial communities of these cropping systems using amplicon sequencing and bioinformatics approaches are currently under way [61,62] and will be fully presented in a future publication.

The SC system was the same as SI except without the history of compost amendments; yet, despite an increased rotation length and use of cover crops relative to the standard SQ rotation, it did not result in consistent differences from SQ regarding yield, disease, or most soil properties, either in earlier studies [24–27] or in the present study. However, there were signs of developing effects, in that, although SC did not show a significantly greater total tuber yield than SQ in any single year, the average value over the four years of the study did show SC with a higher overall yield than SQ, with an increase of about 10%. In addition, soilborne diseases did show some indications of reduction, with SC reducing black scurf and common scab relative to SQ in one of four years, and with an overall reduction in black scurf of about 10% (although not statistically significant). However, this does indicate that incremental changes, such as an additional year of rotation and the addition of cover crops, by themselves may not be enough to result in substantial changes in soil health properties, yield, or disease suppression, or may take considerable time to show such effects. Wood et al. [63] observed, in large-scale, farmer-led studies, that 2 to 5 years of cover crop usage resulted in small but positive impacts on several soil health indicators, including organic matter content, active carbon, aggregate stability, and microbial respiration, but also noted that more years were needed for substantial changes to occur. Other researchers have also noted that significant effects due to increased rotation length and cover crops alone may take many years to develop [10,64,65].

The degradation of soil health properties within the PP nonrotation was also more apparent by this time of the study than in previous assessments, as OM content and microbial indicators were lower than all other systems and had declined substantially from initial levels. Although it was already known that continuous potato resulted in substantial disease problems and declining yields, this study further documented the unsustainable nature of continuous potato cropping, with poor potato yields, higher soilborne disease, and poor soil health issues.

5. Conclusions

In this study, a soil improving cropping system characterized by several years of compost amendments in addition to the use of cover crops and an extended (3-yr) rotation period substantially improved potato yield, the occurrence of soilborne diseases, and various soil health parameters relative to a standard rotation over an extended period. In addition, a 3-yr rotation focused on reducing soilborne diseases through the use of a Brassica green manure and cover crops did maintain low disease levels, as well as improved yield relative to a standard rotation over an extended period of time. Previous work had already established that the use of soil and crop management practices such as extending crop rotations, cover crops and green manures, reduced tillage, and organic amendments, can improve soil health and increase crop productivity, and that they can be integrated into effective cropping systems. What this study has added to that is to show that some effects increase over time or need substantial time to develop, that improvements from inputs such as organic amendments can have long-lasting effects years later, and that such improvements can be maintained or sustained for many years. Of additional importance is that the more practical modified systems continued to provide comparable levels of effectiveness as the original cropping systems. The initial cropping systems established in 2004 for these trials were designed to document the extent of effects that could be achieved through cropping system practices and represented somewhat radical departures from traditional production practices (such as the reduction to only one major cash crop every three years) that may not have been economically sustainable, whereas the modified systems represent less drastic changes (two major cash crops every three years) that can be readily implemented into current production practices. The success of these modified SI and DS systems in maintaining high yields, low disease, and improved soil health relative to other systems indicates that these cropping systems can provide greater sustainability and productivity in potato production systems. This study also demonstrated that the development of improved cropping systems can substantially enhance productivity from the standard cropping system currently used throughout the Northeastern US for potato production.

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