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Use and Effects of Different *Brassica* and Other Rotation Crops on Soilborne Diseases and Yield of Potato †

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Abstract: Soilborne diseases are persistent problems in potato production, resulting in reductions in tuber quality and yield. *Brassica* rotation crops may reduce soilborne potato diseases, but how to best utilize *Brassica* crops in potato cropping systems has not been established. In this research, two two-year trials were established at three different sites with histories of soilborne diseases, and up to six different *Brassica* crops (canola, winter rapeseed, yellow and brown condiment mustards, oriental mustard, oilseed radish, and a mustard blend) and standard rotation crops (ryegrass and buckwheat) were evaluated as rotation and green manure crops. Tuber yield did not vary substantially among the rotation crops, but rotation treatments significantly affected incidence and severity of soilborne diseases at all sites. However, results were variable among sites and years. Perennial ryegrass and mustard blend rotations reduced powdery scab disease by 31–55% relative to other rotations in the only field where powdery scab was a serious problem. Mustard blend, ryegrass, and other *Brassica* rotations also reduced common scab, silver scurf, and black scurf at various sites, but not consistently at all sites. At one site, mustard blend and barley/ryegrass rotations reduced black scurf (by 21–58%) and common scab (by 13–34%) relative to no rotation. Overall, disease control was not correlated with biofumigation potential or rotation crop biomass production. Although both *Brassica* and non-*Brassica* rotations provided disease reduction in potato cropping systems, no single rotation crop performed consistently better than several others.

Keywords: *Solanum tuberosum*; *Brassica* spp.; crop rotation; green manure; black scurf; common scab; powdery scab; mustard; ryegrass

1. Introduction

Many soilborne diseases are persistent, recurrent problems in potato production. These diseases compromise plant growth and vigor, lower tuber quality, and reduce overall tuber marketability. Several soilborne diseases of potato (*Solanum tuberosum*), which are prevalent throughout the Northeastern US and most other potato-producing regions, include: stem canker and black scurf, caused by the fungus *Rhizoctonia solani*; silver scurf, caused by the fungus *Helminthosporium solani*; common scab, caused by the bacterium *Streptomyces scabies*; and powdery scab, caused by the protist-like plasmodiophorid pathogen *Spongospora subterranea* f.sp. *subterranea*.

Powdery scab is of particular concern, as occurrence of this disease has been increasing in the Northeast, as well as several other potato-producing regions [1–5]. Powdery scab causes abundant lesions (pustules) on the tuber surface, directly reducing tuber marketability and potentially reducing yields following additional losses during storage. In addition, the pathogen also infects roots, causing root galls and reductions in plant productivity and yield [4,6]. Moreover, the disease's causal organism, *Spongospora subterranea*, is the sole vector of potato mop-top virus (PMTV), a serious disease that has been observed in potato production systems in Maine and Canada from 2002 on [2,7]. *Spongospora subterranea* is extremely long-lived in the soil, and is thought to persist indefinitely [1,8]. Current control measures using chemicals or cultural practices have not been very effective in managing the pathogen or disease [1,3,9–11].

Although chemical treatments such as soil fumigants and seed treatments have shown some efficacy in reducing many soilborne diseases, their effects have generally been short-lived, and their use has not always been practical or sufficiently effective. Options for effective approaches that could be both economically and environmentally sustainable would be highly desirable. Crop rotations have long been used as a means to help manage soilborne diseases. Thus, an approach with much potential is in making improvements to optimize the disease-suppressive capabilities of rotations to be more effective at suppressing multiple diseases.

Use of *Brassica* (and other related genera) plants as cover and green manure crops has been associated with reductions in soilborne diseases. Crops in the Brassicaceae family, which include broccoli, cabbage, cauliflower, kale, turnip, radish, canola, rapeseed, and various mustards, produce sulfur compounds called glucosinolates that break down to produce isothiocyanates that are toxic to many soil organisms as part of a process referred to as biofumigation [12,13]. This mechanism has been shown to reduce populations of multiple soilborne pathogens [14,15], nematodes [16,17], and weeds [18,19]. Many additional factors, such as soil type, plant growth stage, glucosinolate concentration/isothiocyanate composition, and method of incorporation, play crucial roles in the use of biofumigant rotation crops for disease suppression [12]. *Brassica* crops grown as green manures, in particular, have been shown to be effective in reducing soilborne diseases, and particularly, soilborne potato diseases in numerous field trials [15,20,21]. In addition to the potential disease benefits of biofumigation, studies also show improvements to many soil characteristics, such as increased porosity and organic matter content, which may lead to lower disease levels as well as increased crop yields when *Brassica* crops are used [22].

Brassica (and other) rotation crops may also suppress diseases, through their effects on soil microbial communities and development of suppressive conditions, that are separate from the biofumigation response. Larkin and Honeycutt [23] observed that rotations containing canola and rapeseed (*Brassica napus*) exhibited microbial community characteristics distinct from non-*Brassica* rotations, and these rotations resulted in reduced incidence and severity of *Rhizoctonia* disease in potato, even when the rotations were not incorporated as green manures. In addition, Larkin and Griffin [15] observed that disease suppression was not consistently associated with high glucosinolate-producing crops, and that barley and ryegrass rotations resulted in disease reduction of multiple soilborne diseases of potato that was comparable to that of *Brassica* green manures. Mazzola et al. [24] observed that *B. napus* seed meal amendments suppressed *R. solani* and other related apple replant diseases regardless of the glucosinolate content. Cohen et al. [25] determined that the observed disease suppression was associated with dramatic changes to the total bacteria and actinomycete populations in response to the seed meal amendments.

Although previous research has demonstrated the potential of *Brassicas* to reduce disease, it is not yet known which crops are best for which diseases, how to manage these crops for effective disease reduction, and how to best implement these crops into a potato rotation and production system. One factor of particular importance to growers is whether a full-season green manure crop is needed to achieve disease control. The disadvantage of green manure crops is that it takes the field out of any kind of production for that season. If use of a *Brassica* cash crop, such as condiment mustard or canola, can be effective in reducing disease, or if the *Brassica* crop can be effective as a fall cover crop implemented after a regular seasonal rotation crop, that would give growers more flexibility in how to effectively implement *Brassicas* for disease control into their production system. In other potato-growing regions, such as the western U.S., Brassicas can be grown as fall cover or green manure crops, but in the shorter-growing season of the Northeast, this may not be effective. The intent of this research was to evaluate the effects of a variety of different *Brassica* rotation crops managed in different ways (as green manures, harvested crops, fall cover crops) on several different aspects of potato production, including soilborne diseases and yield, in multiple field settings. Thus, the current field studies were established to assess these aspects of rotation crop selection and management as they relate to disease reduction and tuber yield.

2. Materials and Methods

2.1. Field Sites

Field study sites were established on-farm at two commercial potato farms in Aroostook County, Maine, one located in Central Aroostook and one in Northern Aroostook. At each site, two adjacent or nearby fields were prepared for establishment of rotation crops in 2005 and 2006 (designated as Year 0 and Year 1), respectively, and then potato crops were planted following the rotation crops, in 2006 and 2007 (designated as Year 1 and Year 2), respectively. Thus, at each site, two full two-year rotation cycles were achieved in three field seasons. Both sites had a known previous history of soilborne diseases, including powdery scab, black scurf, common scab, and silver scurf problems. In addition, at a third site located on the USDA-ARS Research Farm at Newport, ME (Southern Penobscot County), a single field was used and monitored through two rotation cycles (2005–2008). Experimental details for each site are explained below.

Central Aroostook Site. Fields were located on a commercial processing and seed stock operation. The soil type was a Caribou gravelly loam (fine-loamy, isotic, frigid, Typic Haplorthod). Prior to the plots being established in June and May of Years 0 and 1, respectively, the fields were planted to potato the previous year and remained fallow post-harvest. The grower's typical two-year rotation was potato followed by canola. Experimental design in both fields was a randomized complete block consisting of five rotation treatments in each of four replicated blocks. In Year 0, plot size was 3.1 m × 18.3 m and in Year 1 plot size was 6.1 m × 30.5 m (smaller plot size due to available land limitations). *Brassica* rotation crops were planted with a cone seeder at 8 kg/ha on 21 and 22 June of Years 0 and 1, respectively.

Northern Aroostook Site. Fields were located on a commercial seed stock operation. Soil type was a Plaisted gravelly loam (coarse loamy, isotic, frigid, Oxyaquic Haplorthod). The fields had been in potato the previous year and remained fallow post-harvest. The grower's typical two-year rotation was buckwheat followed by potato. The experimental design was a randomized complete block with eight rotation treatments in each of four replicate blocks (plot size 10.7 m × 45.7 m and 10.7 m × 30.5 m in Years 0 and 1, respectively). *Brassica* rotation crops were planted using the grower's box-spreader at 9 kg/ha with 34 kg/ha 10-10-10 fertilizer on 21 and 22 June in Years 0 and 1, respectively.

Newport Site. This trial was conducted on previously established rotation plots (two-year rotation study begun in 2001) with a history of Rhizoctonia and common scab. Soil at this site was a Nokomis silt loam (coarse loamy, mixed, frigid, Typic Haplorthod). The experimental design was a randomized complete block consisting of four replicate blocks with three rotation crop treatments (Table 1). Each rotation plot was 3.7 m × 18.3 m. This study also included a nonrotation control of continuous potato (cultivar "Shepody"), with potato planted each year. Rotation crops were planted in June 2005 and 2007, with the *Brassica* crop planted at approximately 8 kg/ha.

Table 1. Rotation crops evaluated for effects on soilborne potato diseases and yield at Central and Northern Aroostook and Newport field sites.

		Relative	Rel.	Site Plantings					
		gluc.	gluc.	Central Ar.		North Ar.		Newport	
Rotation Crop	**Scientific Name**	**Content** [y]	**Rank** [y]	**Yr 0**	**Yr 1**	**Yr 0**	**Yr 1**	**Yr 0**	**Yr 1**
Canola "Hyola 420"	*Brassica napus*	Low	1	X [z]	X	X	X	–	–
Rapeseed "Dwarf Essex"	*Brassica napus*	Moderate	2	X	X	X	X	–	–
Yellow mustard "Ace"	*Sinapis alba*	Moderate	3	X	X	X	X	–	–
Oilseed radish	*Raphanus sativa*	Moderate	4	–	–	X	–	–	–
Brn mustard "Duchess"	*Brassica juncea*	High	5	–	–	–	X	–	–
Mustard blend	*S. alba/B.juncea*	High	6	X	X	X	X	X	X
Oriental mustard	*Brassica juncea*	High	5	–	–	X	X	–	–
Buckwheat	*Fagopyrum sagittatum*	None	0	–	–	X	X	–	–
Bkwt/red clover	*F. sag./T. pratense*	None	0	–	–	–	X	–	–
Perennial ryegrass	*Loilium perenne*	None	0	X	X	–	–	X	X

[y] Relative gluc. content and rank refer to glucosinolate, which is a compound produced by *Brassica* crops that is primarily responsible for the biofumigation effect, and the relative content or rank for that crop. Content grouped from none to high, and ranked from 0 to 6; [z] An "X" indicates that this crop was grown at this site and year (Yr), whereas "–" indicates crop not grown here. Canola is the grower's standard rotation crop at the Central Aroostook site, buckwheat is the standard rotation crop at the Northern Aroostook site, and barley underseeded with ryegrass was the standard rotation crop at Newport. At Newport only, an additional treatment of a nonrotation control (continuous potato) was also grown for comparison with the rotation crop treatments.

2.2. Rotation Crops and Rotation Crop–Year Management

The following *Brassica* rotation crop treatments were assessed in multiple trials: "Hyola-420" untreated canola (*Brassica napus*), "Dwarf Essex" winter rapeseed (*Brassica napus*), "Ace yellow" condiment mustard (*Sinapis alba*), "Caliente 119" high-glucosinolate (High-GSL) white/oriental mustard blend (*Sinapis alba/Brassica juncea*), and oriental mustard (*Brassica juncea*). Oilseed radish (*Raphanus sativa*) was planted at Northern Aroostook in Year 0 only (due to lack of seed in the following year) and was replaced by "Duchess Brown" condiment mustard (*Brassica juncea*) in Year 1. The non-*Brassica* rotation crops included buckwheat (*Fagopyrum sagittatum*), buckwheat underseeded with mammoth red clover (*Trifolium pratense L.*), perennial ryegrass (*Lolium perenne* L.), and barley (*Hordeum vulgare*) underseeded with perennial ryegrass, which represented the standard rotation crop at each of the three sites, respectively. Table 1 shows characteristics of the rotation crops and which crops were planted at each field site and year. Plots were managed according to standard management practices by the grower throughout the growing season. Plots were monitored throughout the season for germination and stand quality.

Rotation crops that normally would be harvested for seed or forage rather than incorporated as a green manure were handled that way, so the yellow condiment mustard and ryegrass at the Central Aroostook site were harvested/mowed but not incorporated, and barley/ryegrass at Newport was not incorporated. All other rotations were mowed with a flail mower, and then immediately incorporated with a moldboard plow as green manures.

Above-ground rotation crop biomass samples were taken from each rotation plot in August prior to incorporation at each field site. All plants within two randomly-determined 1/8 m^2 quadrats were removed at 5 cm above the ground. Biomass samples were weighed immediately and also after approximately one week of drying. Measurements were taken when plants were fully mature, but senescence had not occurred. Rotation crops were mowed/incorporated on 10 and 20 August in Years 0 and 1, respectively, at the Central Aroostook site, and 4 and 20 August, at the Northern Aroostook site.

The original intent of the study was to also have a fall cover crop of rapeseed ("Dwarf Essex") following the summer rotation crops and planted on half of each plot (as a split-block treatment). This was attempted each year at the Central Aroostook site and in Year 0 at the Northern Aroostook site, with rapeseed planted with a cone seeder at 8 kg/ha on 14 and 18 September, in Years 0 and 1 at the Central Aroostook site, respectively, and on 26 August, Year 0 at the Northern Aroostook site.

Stand emergence and growth was extremely poor both years, and post-germination plant growth was minimal. Data from these failed cover crops were not used in the analyses. In addition, at the Newport site, a series of timed plantings of rapeseed were made on 1 and 15 August and 1 and 15 September 2006 in demonstration plots just to determine feasibility of the fall rapeseed cover crop. Only the 1 August planting resulted in reasonable germination and substantial plant growth, with all later plantings failing to produce adequate biomass for use as a cover crop. Thus, further use of rapeseed as a fall cover crop was dropped from the study.

2.3. Potato Crop–Year Management

In the following spring after rotation crop treatments, all plots were planted to potato. At the Central Aroostook site, cultivar "Andover" (used for processing) was planted on 28 May in Year 1, potato variety "Dark Red Norland" (seed stock) was planted on 15 May in Year 2. At the Northern Aroostook site, all plots were planted to a Frito-Lay® proprietary seed potato cultivar in both years, on 1 and 3 June in Years 1 and 2, respectively. At the Newport site, all plots were planted to potato cultivar "Shepody" on 7 June and 15 May in Years 1 and 2, respectively. The potato plants were managed by the grower using conventional management practices common to the region. Potato plants and roots were assessed on-site for stem and stolon canker lesions and other root diseases in mid-August at each site. Two plants (including roots and tubers) from each of two middle-rows (for a total of four plants per plot) were hand-dug and above-ground biomass was removed, after which the stems and stolons were rinsed in water to remove excess soil and to make the lesions easier to identify. The rating scale was as follows: 0 = no symptoms present; 1 = mild discolorations on stems and/or stolons; 2 = distinct lesions visible, covering <25% of the stem or stolon circumference; 3 = lesions extending around 25–75% of stem or stolon circumference; 4 = greater than 75% lesion coverage of stem or stolon circumference; 5 = stem/stolons necrotic, complete desiccation.

Potato tubers were harvested from all plots in September of each year. From each plot, a 3.1 m section from each of two separate middle plot rows was harvested by hand (6.2 m total per plot). In Year 1 at the Northern Aroostook site, the grower independently harvested all plots before the intended hand-digging was scheduled to occur, and it was not possible to obtain yield data from these samples (disease ratings only). All harvested tubers were washed, weighed, and graded according to size. Tubers larger than 4.7 cm diameter were considered marketable by the growers. At the Central Aroostook and Newport sites in Year 1 only, tubers were graded as small, medium, and large according to the categories <4.7 cm, 4.7 cm–5.7 cm, and >5.7 cm. At all other sites, tubers were just classified as marketable (>4.7 cm) or unmarketable (<4.7 cm). All yield values were converted to represent Mg/ha. After tubers were washed and graded for size and abnormalities, they were visually assessed for incidence and severity of tuber diseases (if present). A random sample of 30 tubers per plot was used for these assessments, with severity determined as the percentage of tuber surface area that was covered by sclerotia or lesions of the particular disease. A severity rating of greater than 2% tuber coverage was used as a threshold above which most diseases become a problem for marketability. Thus, incidence of tubers with greater than 2% severity represented the proportion of tubers that are particular problems for growers as they could be rejected due to disease and was referred to as the incidence of substantial disease. This measure of incidence was used for reporting most disease data. However, where disease incidence and severity were particularly low, the measure of total incidence (percentage of tubers showing any disease symptoms) was used.

2.4. Statistical Analysis

Data from rotation crop biomass, disease ratings, and tuber yield assessments were analyzed by analysis of variance using the appropriate factor and interaction structure for the randomized complete block or split-block design, as needed. All experiments used four replications of each rotation treatment and data from each trial were analyzed separately using SAS Proc GLM (version 9.4, SAS Institute, Cary, North Carolina). Mean separation was accomplished using Fisher's protected least significant difference (LSD) test. Correlation assessments among the different parameters were derived from Pearson's Product-Moment Correlation Coefficient matrices. A parameter based on the relative ranking of glucosinolate production (0–6) for each rotation crop, as well as a parameter that combined the glucosinolate ranking with rotation biomass production, was used as an estimate of the potential role of glucosinolate for correlation analysis purposes. Significance for all tests was evaluated at $P < 0.05$.

3. Results

3.1. Rotation Crop Development and Biomass Production

Central Aroostook Site. Germination and emergence were excellent for most rotation crops in both years. The perennial ryegrass stands had substantial weed growth, most likely due to reduced germination and emergence rates. In Year 0, biomass production ranged 4300–18,240 kg ha^{-1} (fresh weight) when assessed in August, prior to incorporation. Canola produced the highest fresh weight out of all rotations, and ryegrass the lowest, each significantly different from all other rotations (Figure 1A). Dry weights also followed similar relationships. Yellow condiment mustard and ryegrass treatments were mowed, but not incorporated and left as residue until the following spring. In Year 1, biomass production ranged 6600–18,500 kg ha^{-1} when assessed in August, prior to incorporation. Rapeseed produced the highest fresh weight out of all rotations, and ryegrass and the mustard blend the lowest (Figure 1B). Dry weights followed similar relationships.

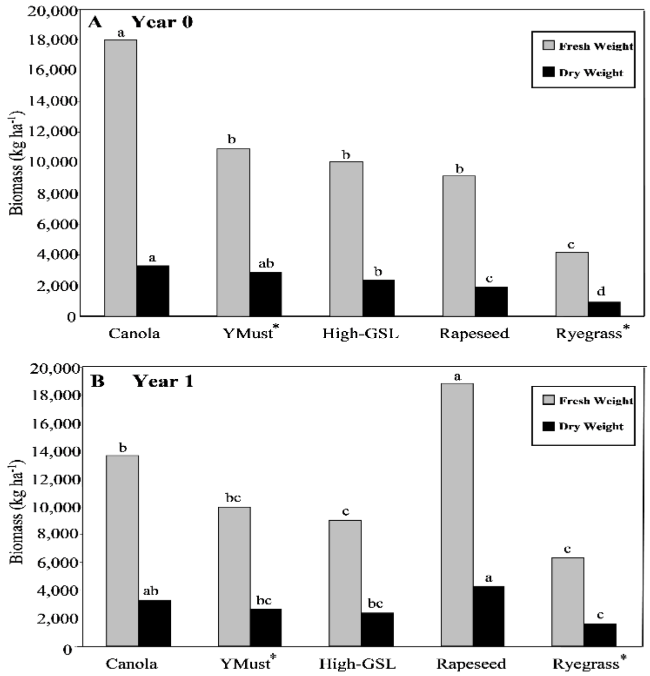

Figure 1. Fresh and dried weights of rotation crop biomass from the Central Aroostook site in (**A**) Year 0 and (**B**) Year 1 of the trial, respectively, taken immediately prior to incorporation. Values were derived from 1/8 m^2 quadrat samples. Means for each sample type (fresh and dry) for each year with the same letter are not significantly different according to Fisher's protected LSD at $P = 0.05$. * Yellow mustard and ryegrass were not incorporated and left on soil surface as residues.

Northern Aroostook Site. All rotations had excellent germination, emergence and growth in both rotation crop years. In Year 0, biomass production ranged 12,500–27,400 kg ha^{-1} when assessed in August. Yellow condiment mustard stands had insect damage, most likely flea beetles. Buckwheat produced generally higher above-ground biomass (both fresh and dry weights) than the *Brassica* crops, but was significantly greater than only the mustard blend (fresh and dry weight) and oilseed radish (dry weight only). Biomass levels were comparable among all *Brassica* crops (Figure 2A). In Year 1, rotation crop biomass ranged 10,260–29,640 kg ha^{-1} when assessed in August. Buckwheat produced higher amounts of biomass (both fresh and dry weights) than all other rotations (Figure 2B). Among the *Brassica* rotations, mustard blend produced lower biomass than most other *Brassicas* (fresh and dry weights).

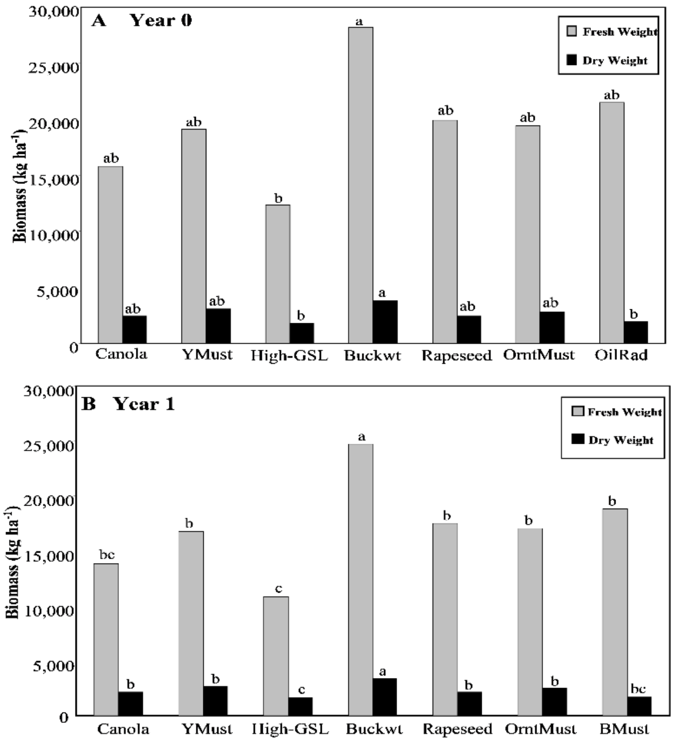

Figure 2. Fresh and dried weights of rotation crop biomass from the Northern Aroostook site in (**A**) Year 0 and (**B**) Year 1 immediately prior to incorporation. Values were derived from 1/8 m^2 quadrat samples. Means for each sample type (fresh or dry) for each year with the same letter are not significantly different according to Fisher's protected LSD at $P = 0.05$.

Newport Site. Establishment of the mustard blend stands was initially poor. After low emergence and germination rates were noted, the plots were re-seeded by hand. However, subsequent weed pressure limited the growth of the mustard plants. Germination and stands of the other crops were very good.

3.2. Soilborne Disease

Central Aroostook Site. In both potato production years, incidence of stem and stolon canker on potato plants was very low and no significant differences were observed among rotations (data not shown). In Year 1, observed tuber diseases included common scab, silver scurf, and black scurf, and there were significant differences among rotation crops. Common scab was present at moderate levels (severity of 1.8–2.3% and incidence of 50–70%), with lower levels of silver scurf (severity of 0.6–1.8% and incidence of 10–20%), and very low levels of black scurf (severity of 0–0.4% and incidence of 0–10%). Ryegrass rotation crop was the only treatment to significantly reduce common scab severity and incidence (Table 2), with reductions of 18–25% relative to other rotations. Silver scurf severity was lower with yellow mustard and high-GSL mustard blend relative to canola and rapeseed treatments, with reductions of 28–60% observed. Similar results were observed in silver scurf incidence, where higher levels in canola and winter rapeseed occurred relative to most other rotations. For black scurf, although disease levels were low, ryegrass and mustard blend treatments resulted in significantly lower disease severity and incidence, with no black scurf detected on tubers in the mustard blend treatment.

In Year 2, observed tuber diseases were primarily common scab and powdery scab. Disease severity was moderate to substantial (average severity 1.3–3.0%). Incidence of substantial common scab was high in all plots (>50%), with no rotations significantly reducing scab severity or incidence relative to each other, although the mustard blend had nominally lower severity and incidence than the rest. Powdery scab was a much more prominent problem in Year 2 compared to Year 1 at this site. Severity and incidence of powdery scab were significantly lower for the mustard blend and ryegrass rotations than most other treatments (Table 2), with reductions of 31–55%. Canola and rapeseed had higher severity and incidence than other rotations.

Table 2. Development of soilborne potato diseases at the Central Aroostook site as affected by previous rotation crop in Year 1 and Year 2 of potato production.

	Common Scab		**Silver Scurf**		**Black Scurf**	
Rotation Treatment	**Severity** [x]	**Incidence** [y]	**Severity** [x]	**Incidence** [y]	**Severity** [x]	**Incidence** [y]
Year 1						
Canola	2.18 a [z]	62.9 a	1.40 ab	20.0 a	0.40 a	10.4 a
Yellow mustard	2.28 a	69.6 a	0.57 c	10.4 c	0.22 ab	4.6 bc
Rapeseed	2.33 a	63.3 a	1.83 a	17.4 ab	0.37 a	6.7 ab
Mustard Blend	2.30 a	66.7 a	0.86 c	12.5 bc	0.00 c	0.0 d
Ryegrass	1.76 b	52.1 b	0.92 bc	13.8 bc	0.05 bc	1.3 cd
Year 2	Common scab		Powdery scab			
Canola	2.55 a	57.9 a	2.59 a	25.4 ab		
Yellow mustard	2.28 a	51.2 a	2.03 bc	20.4 bc		
Rapeseed	2.46 a	53.3 a	2.93 a	27.5 a		
Mustard Blend	2.17 a	47.5 a	1.48 c	15.4 c		
Ryegrass	2.48 a	57.9 a	1.31 c	17.5 c		

[x] Severity based on percent of tuber surface covered by lesions; [y] Incidence of tubers (percentage) with severity rating greater than 2%; [z] Means within columns for each year followed by the same letter are not significantly different according to Fisher's protected LSD at $P = 0.05$.

Northern Aroostook Site. Stem and stolon canker incidence on potato plants was very low and no significant differences were observed among rotation treatments in either potato crop year (data not shown). Common scab and powdery scab were the primary tuber diseases observed in both potato crop years. In Year 1, although severity of tuber diseases was generally low (less than 1.5% of tuber surface affected), significant differences among rotations were observed (Table 3). Canola, mustard blend, and buckwheat rotations resulted in significantly lower common scab severity than most of the other rotations, with reductions of 23–60%. Similarly, incidence of common scab in the canola and mustard blend rotations was significantly lower relative to oilseed radish and rapeseed rotations. Although powdery scab levels were low, oilseed radish and yellow mustard rotations resulted in significant reductions in the severity and incidence of powdery scab relative to the other rotations, whereas powdery scab was highest in the mustard blend and oriental mustard treatments. In Year 2, common scab severity was much higher compared to Year 1, with severity values averaging 3–4.5% (Table 3). Several rotations, including buckwheat, buckwheat/red clover, rapeseed, mustard blend, and oriental mustard resulted in lower disease incidence and severity relative to canola. Powdery scab severity and incidence was very low, averaging less than 20% incidence and 0.35% surface coverage throughout all treatments, but mustard blend and buckwheat/clover treatments resulted in lower incidence and severity levels than all other rotations, averaging less than 0.12% severity and 10% incidence.

Newport Site. Stem canker, black scurf, and common scab were the predominant soilborne diseases observed at this site in both potato production years. Both the mustard blend and barley/ryegrass rotations significantly reduced the incidence and severity of all diseases (stem canker, black scurf, and common scab) relative to the potato nonrotation control in Year 1, with the mustard blend reducing canker and scurf by 31–68% and common scab by 15–34%, and barley/ryegrass reducing canker and scurf by 21–62% and common scab by 14–30% (Table 4). Total disease severity for all diseases combined was also similarly reduced in the mustard blend and barley/ryegrass rotation. Although the mustard blend resulted in slightly lower disease levels overall, there was no significant difference between effects due to the mustard blend and barley/ryegrass. Similar results were observed for canker and black scurf in Year 2, but with higher levels of disease observed. Common scab, however, was less severe, and no significant differences among rotation treatments were observed. Total disease severity did show overall reductions with mustard blend and barley/ryegrass rotations.

Table 3. Development of soilborne potato diseases at the Northern Aroostook site as affected by previous rotation crop in Year 1 and Year 2 of potato production.

	Year 1				Year 2			
	Common Scab		Powdery Scab		Common Scab		Powdery Scab	
Rotation Crop	**Severity [w]**	**Incidence [x]**	**Severity [w]**	**Incidence [x]**	**Severity [w]**	**Incidence [y]**	**Severity [w]**	**Incidence [x]**
Canola	0.61 c [z]	55.0 c	0.57 b	36.7 ab	4.36 a[c]	30.0 a	0.25 ab	13.3 a
Yellow mustard	0.93 bc	75.0 abc	0.28 c	18.3 cd	4.33 ab	23.7 ab	0.34 a	19.2 a
Rapeseed	1.23 ab	91.7 a	0.43 bc	35.0 bc	3.50 c	15.8 bc	0.29 ab	15.0 a
Radish/Brn must	1.12 ab	81.7 ab	0.04 d	3.3 d	4.18 ab	25.8 ab	0.22 ab	18.3 a
Oriental mustard	1.49 a	75.0 abc	0.85 a	53.3 a	3.28 c	15.8 bc	0.25 ab	16.7 a
Mustard blend	0.59 c	55.0 c	0.80 a	45.3 ab	3.77 bc	15.8 bc	0.11 b	9.1 b
Buckwheat [a]	0.68 c	60.8 bc	0.51 b	34.2 bc	3.52 c	17.5 bc	0.24 ab	14.2 a
Bkwt/red clover	–	–	–	–	3.36 c	14.2 c	0.12 b	9.2 b

[w] Severity based on percent of tuber surface covered by lesions; [x] Incidence of tubers (percentage) with scab lesions; [y] Incidence of tubers (percentage) with severity rating greater than 2%; [z] Means within columns followed by the same letter are not significantly different according to Fisher's protected LSD at $P = 0.05$.

Table 4. Development of soilborne potato diseases at the Newport site as affected by previous rotation crop in Year 1 and Year 2 of potato production.

	Canker [w]	Black Scurf		Common Scab		Total Disease
Rotation Treatment	**Severity**	**Severity [x]**	**Incidence [y]**	**Severity [x]**	**Incidence [y]**	**Severity [x]**
Year 1						
Mustard blend	0.94 b [z]	1.00 b	15.8 b	3.14 b	76.2 b	4.14 b
Barley/ryegrass	0.96 b	1.03 b	13.7 b	3.22 b	78.7 b	4.22 b
Potato	1.40 a	1.59 a	41.7 a	3.79 a	92.5 a	5.38 a
Year 2						
Mustard blend	1.43 b	0.99 b	20.8 b	1.96 a	74.2 a	2.95 b
Barley/ryegrass	1.71 b	1.20 b	27.5 b	1.93 a	72.1 a	3.14 b
Potato	2.24 a	2.41 a	79.6 a	1.92 a	74.6 a	4.33 a

[w] Canker refers to stem and stolon canker. Severity assessed by average of the disease rating index on a scale of 0–5 per plant; [x] Severity based on percent of tuber surface covered by lesions; [y] Incidence of tubers (percentage) with severity rating greater than 2%; [z] Means within columns for each year followed by the same letter are not significantly different according to Fisher's protected LSD at $P = 0.05$.

3.3. Tuber Yield

Central Aroostook Site. In Year 1, when processing variety "Andover" was grown, significant tuber yield differences among treatments were observed in total and marketable yield categories, as well as the large size class (Table 5). Canola and winter rapeseed plots produced significantly higher total yield and marketable yield (tubers exceeding 4.7 cm diameter) relative to the mustard blend, with observed increases of 13–22%. Additionally, canola produced higher yields of large size-class tubers relative to the ryegrass treatment. In Year 2, when the cultivar "Dark Red Norland" was grown, slightly higher total yields were observed relative to Year 1, although a higher proportion of cull tubers resulted in slightly lower marketable yields (Table 5). No significant differences were observed in total or small size yields among rotation treatments, but ryegrass averaged significantly higher marketable yields than winter rapeseed. Growth of the fall-planted cover crop (rapeseed) was unsuccessful in both years, therefore, no significant effects of the fall cover crop on tuber yield or disease were observed.

Table 5. Average potato tuber yield in various size classes in addition to marketable and total yield as affected by previous rotation crop treatments at the Central Aroostook site in potato Years 1 and 2.

	Tuber Yield (Mg ha^{-1})							
	Year 1					Year 2		
Rotation Crop	**Small** [v]	**Medium** [w]	**Large** [x]	**Marketable** [y]	**Total**	**Small** [v]	**Marketable** [y]	**Total**
Canola	3.36 a [z]	11.2 a	16.3 a	27.5 a	30.0 a	6.60 a	23.9 ab	30.5 a
Yellow mustard	3.24 a	10.7 a	13.8 ab	24.5 bc	27.7 ab	6.03 a	24.1 ab	30.1 a
Rapeseed	4.22 a	10.7 a	15.0 ab	25.7 ab	29.9 a	6.93 a	23.1 b	30.0 a
Mustard blend	3.34 a	9.7 a	13.2 ab	22.6 c	25.9 b	7.82 a	24.6 ab	31.8 a
Ryegrass	4.04 a	11.2 a	12.8 b	23.8 bc	27.8 ab	6.25 a	25.6 a	31.8 a

[v] Small size class consisted of tubers <4.7 cm diameter; [w] Medium size class consisted of tubers 4.7–5.6 cm diameter; [x] Large size class consisted of tubers >5.6 cm diameter; [y] Marketable class consisted of tubers in the medium and large size classes combined (>4.7 cm); [z] Means within columns followed by the same letter are not significantly different according to Fisher's protected LSD at $P = 0.05$.

Northern Aroostook Site. Due to an early unanticipated and unmonitored harvest in Year 1, yield data were not available for rotation treatments that year. In Year 2, there were no significant treatment effects on any category of tuber yield at this site (Table 6). The canola and rapeseed rotations had slightly higher total and marketable yields, but were not significantly different than any other rotations.

Table 6. Average potato tuber yield of marketable, small (cull), and total tuber yield as affected by previous rotation crop treatments at the Northern Aroostook site in potato Year 2.

	Yield (Mg ha^{-1})		
Rotation Crop	**Small** [x]	**Marketable** [y]	**Total**
Canola	6.84 a [z]	31.8 a	38.6 a
Yellow mustard	5.39 a	30.2 a	35.6 a
Rapeseed	6.33 a	31.6 a	37.9 a
Brown mustard	6.64 a	29.1 a	35.8 a
Oriental mustard	6.38 a	29.9 a	36.2 a
Mustard blend	5.20 a	31.0 a	36.2 a
Buckwheat	5.92 a	29.9 a	35.8 a
Bkwt/red clover	6.12 a	30.8 a	36.9 a

[x] Small size class consisted of tubers <4.7 cm diameter; [y] Marketable class consisted of tubers in the medium and large size classes combined (>4.7 cm); [z] Means within columns followed by the same letter are not significantly different according to Fisher's protected LSD at $P = 0.05$.

Newport Site. Potato tuber yield was significantly affected by rotation crop treatments, with both the mustard blend and barley/ryegrass rotations resulting in significantly higher total and marketable yields, as well as higher yields of medium and large size classes than the potato nonrotation control in Year 1 (Table 7). The barley/ryegrass rotation also averaged significantly higher total and marketable yields than the mustard blend rotation. The mustard blend rotation averaged yields of 14% and 32% higher than the potato control, for total and marketable yields, respectively. The barley/ryegrass rotation, however, averaged an additional 9–11% greater than the mustard blend rotation (i.e., 24% and 48% greater than the potato control) for total and marketable yields. In Year 2, only the barley/ryegrass rotation resulted in significantly higher total and marketable yields than the potato control with increases of 13–17%. Although the mustard blend showed nominal increases (of 11–12%) over the potato control for both total and marketable yield, these differences were not quite statistically significant (Table 7).

Table 7. Average potato tuber yield in various size classes, marketable and total yield as affected by previous rotation crop treatments at the Newport site in potato Years 1 and 2.

	Yield (Mg ha^{-1})							
	Year 1					Year 2		
Rotation Treatment	Small [v]	Medium [w]	Large [x]	Marketable [y]	Total	Small [v]	Marketable [y]	Total
Mustard blend	9.8 a [z]	12.0 b	7.0 a	19.0 b	28.8 b	5.0 a	17.5 ab	22.5 ab
Barley/ryegrass	10.3 a	13.6 a	7.4 a	21.1 a	31.4 a	4.7 a	18.2 a	22.9 a
Potato	10.9 a	10.0 c	4.4 b	14.3 c	25.3 c	4.7 a	15.6 b	20.3 b

[v] Small size class consisted of tubers <4.7 cm diameter; [w] Medium size class consisted of tubers 4.7–5.6 cm diameter; [x] Large size class consisted of tubers >5.6 cm diameter; [y] Marketable class consisted of tubers in the medium and large size classes combined (>4.7 cm); [z] Means within columns followed by the same letter are not significantly different according to Fisher's protected LSD at $P = 0.05$.

3.4. Parameter Correlations

Rotation crop biomass (fresh weight) prior to incorporation was positively correlated with tuber yield at both Aroostook sites, as total harvested tuber yield ($r = 0.474$; $P = 0.01$) and marketable weight ($r = 0.445$; $P = 0.02$) for both years combined at the Northern Aroostook site, and as total harvested tuber yield ($r = 0.316$; $P = 0.04$), marketable yield ($r = 0.374$; $P = 0.02$), and yield of large size-class tubers ($r = 0.328$; $P = 0.04$) at the Central Aroostook site in Year 1, but not Year 2, or the combined analyses for Years 1 and 2. Rotation crop biomass was also positively correlated with common scab severity and incidence ($r = 0.236$ and 0.311; $P = 0.03$ and 0.005, respectively) at Central Aroostook in both years combined. Relative ranking of expected glucosinolate levels or the combination of glucosinolate rank and rotation biomass production was not correlated with any measures of disease assessment at any of the sites ($P > 0.05$). However, glucosinolate rank was negatively correlated with total and marketable tuber yield ($r = -0.241$ and -0.218; $P = 0.03$ and 0.05, respectively) at Central Aroostook for both years combined. In addition, disease severity of common scab was negatively correlated with total and marketable tuber yield ($r = -0.205$ and -0.409; $P = 0.05$ and 0.002, respectively) at Central Aroostook over both years and was also negatively correlated with powdery scab incidence and severity ($r = -0.37$ and -0.32; $P = 0.008$ and 0.02, respectively) at the Northern Aroostook site over both years.

4. Discussion

Several rotation crop treatments indicated capabilities for reducing multiple soilborne diseases, although the results were not always consistent from one site to another or from one year to the next. Although no single rotation provided consistent soilborne disease control, multiple rotations were observed to reduce certain diseases. The high-GSL mustard blend generally had the most significant effects on reducing soilborne diseases throughout the study, where reductions were observed in common scab (Northern Aroostook Year 1), powdery scab (Central Aroostook Year 1 and Northern Aroostook Year 2), and silver scurf and black scurf (Central Aroostook Year 1) compared to other rotations, and stem canker, black scurf, and common scab at Newport Year 1 and canker and black scurf at Newport Year 2 relative to a nonrotation control. Overall, the mustard blend was effective in reducing disease in 11 out of 15 disease interactions. Other *Brassicas* reduced diseases at one site or another, including winter rapeseed (reductions of common scab and powdery scab at Northern Aroostook), yellow condiment mustard (reductions of silver scurf and powdery scab at Central Aroostook Year 1), oilseed radish (reductions of powdery scab at Northern Aroostook Year 1), oriental mustard (reductions of common scab at Northern Aroostook Year 2), and canola (reductions of common scab at Northern Aroostook Year 1). However, the non-*Brassica* crops (perennial ryegrass, buckwheat and buckwheat/clover) also showed significant reductions in diseases comparable to those of the mustard blend and other *Brassicas* at some locations (ryegrass reduced common scab, silver scurf, black scurf, and powdery scab at Central Aroostook, buckwheat and buckwheat/clover reduced common scab and powdery scab at Northern Aroostook). However, no rotations reduced common scab at Central Aroostook in Year 1.

Perennial ryegrass and the mustard blend rotations significantly reduced the incidence and severity of powdery scab disease at the only field site where powdery scab was a substantial problem (Central Aroostook Year 1), with reductions of 31–55% relative to other rotations. This indicates that both a high-GSL *Brassica* crop and a non-*Brassica* grass crop can substantially reduce disease caused by this pathogen. Mustard blend also reduced powdery scab somewhat at Northern Aroostook in Year 2, although disease levels were very low. However, in Year 1 at Northern Aroostook, mustard blend was responsible for among the higher disease levels observed, although again, overall disease levels were low that year. Oilseed radish also substantially reduced powdery scab in the one year it was grown (Northern Aroostook Year 1), which may be worth further investigation. Larkin and Griffin [15] demonstrated that Indian mustard (*Brassica juncea*), canola, rapeseed, and "Lemtal" ryegrass rotations reduced the incidence and severity of powdery scab by 16–40% in previous field trials. These studies also suggested that some *Brassica* crops may provide better control for powdery scab (such as Indian or oriental mustard), while others (canola, rapeseed) may provide better control for black scurf and *Rhizoctonia* diseases. Larkin and Griffin [15] indicated that canola, rapeseed, and yellow mustard reduced severity and incidence of black scurf by 48–78% in those studies, which are consistent with long-term field studies that demonstrate the effectiveness of canola and rapeseed rotations to suppress levels of *Rhizoctonia* potato diseases [23]. In the current study, no distinct separation among rotation crops was observed regarding preferential control of specific pathogens, although black scurf levels were consistently low at all field sites.

It should be noted that these trials represent results based on a single year of a rotation crop grown prior to potato, and that to fully evaluate the more long-term effects of these rotation crops, additional testing over multiple rotation cycles is needed. In previous field studies, Brassica crops used as rotation or green manure crops reduced black scurf and common scab over multiple cropping cycles and years [26–28]. In other studies, two-year rotations with a variety of different crops (alfalfa, oats, vetch, lupine, buckwheat, and ryegrass) have all been observed to reduce the incidence and/or severity of some soilborne diseases, such as stem lesions of *R. solani* by as much as ~50–80% relative to continuous potato [29,30]. Single-season green manure treatments of buckwheat or canola have resulted in significantly less Verticillium wilt and marginally less common scab as well as increased potato yield relative to fallow control plots [31]. In these experiments, green manure treatments were also associated with an increase in the density and pathogen-inhibitory activity of indigenous Streptomycetes toward multiple soilborne potato pathogens (*S. scabies*, *V. dahliae*, *F. oxysporum*, and *R. solani*). Thus, it is not surprising that ryegrass or buckwheat rotations, as observed in this study, can be effective in reducing soilborne diseases.

Canola and rapeseed rotations in the current research resulted in higher yields in Year 1 at the Central Aroostook site, and both the mustard blend and barley/ryegrass rotations resulted in significantly higher yields relative to a continuous potato system at the Newport site. Overall, however, rotation crops did not greatly affect tuber yield. There was some indication that the high-GSL mustard blend may have depressed yield slightly, with lower yields at the Central Aroostook and Newport sites in Year 1 than some other rotations. In addition, relative glucosinolate rank was negatively correlated with yield at Central Aroostook over both site years. Larkin and Honeycutt [23] reported that total and marketable yields were negatively correlated with black scurf incidence. In this study, common scab severity was negatively correlated with total and marketable tuber yield at some sites.

The parameter most consistently associated with higher yields was rotation crop biomass, which was correlated with total and marketable yield at both the Central and Northern Aroostook sites. This suggests that the increased organic matter added through incorporation of green manures may be related to yield improvements, which is consistent with numerous reports [31–33]. Cover crops are known to improve productivity and soil properties [26,34], but green manures may have even greater effects [20]. Green manures are known to increase microbial biomass and activity and soil microbial community characteristics [26,27,35], and have also been shown to change soil microbial communities in ways that are distinctly different from other organic amendments [36]. Friberg et al. [37] also observed that incorporation of mustard residues consistently resulted in greater effects on soil microbial communities and greater reductions in soilborne diseases than other types of organic amendments. In a previous study examining different rotation crops (including Brassicas) managed as green manures vs. cover crops, all crops assessed were more effective at both increasing yield and reducing soilborne diseases when managed as a green manure than as a cover crop, and the known disease-suppressive crops (particularly mustard blend) were most effective of all [38].

Although disease reductions due to the different rotation crops were variable, there was no clear association between either rotation crop biomass or relative crop glucosinolate levels and disease control. For example, at the Central Aroostook site, ryegrass produced the lowest crop biomass in both years and also contains no glucosinolate compounds, but was most effective in reducing common scab in Year 1 and reduced powdery scab comparable to the high-GSL mustard blend in Year 2. As further support of these observations, relative crop glucosinolate rank, rotation crop biomass, and the interaction of the rank and biomass parameters were not correlated with disease parameters at any of the sites. Such correlation analyses help determine the overall relationships across all rotation treatments and provide information on overall trends and mechanisms. These results do not support the notion that disease control is closely associated with glucosinolate levels or biofumigation potential of the rotation crops. In addition, in Year 1, ryegrass biomass was not incorporated, yet still resulted in substantial disease control, indicating that incorporation of the rotation crops as green manures was also not necessarily associated with improved disease control.

The capability of low glucosinolate *Brassica* crops and non-*Brassica* crops to reduce soilborne diseases suggests that a factor other than the toxicity of glucosinolate-derived compounds is an important mechanism of action in reducing soilborne diseases. Previous research has suggested that specific rotation crop effects on soil microbial communities may be at least as important, if not more important, than biofumigation in the reduction of soilborne diseases. Mazzola et al. [24] used *B. napus* seed meal amendments at varied rates and reported suppression of *R. solani* and other related apple replant diseases, regardless of the glucosinolate content. The observed disease suppression was associated with dramatic changes to the total bacteria and actinomycete populations in response to the seed meal amendments, and Cohen et al. [25] reported that additional changes within the microbial communities, including increased populations of nitrifying bacteria, were associated with disease suppression. Larkin and Honeycutt [23] defined several associations between multiple soil microbial community characteristics, tuber yield, and *Rhizoctonia* potato diseases.

Establishment of winter rapeseed as a fall cover crop, as has been successfully implemented in other potato-growing areas, was not successful at any of the three sites in this study. Additional attempts at establishing a fall *Brassica* cover crop at Presque Isle and Newport, ME locations over the past few years have also been unsuccessful when planted later than Mid-August (unpublished data). Planting dates of the fall rapeseed crops ranged from late August to mid-September in these trials, which are typical of the period available for fall planting following most summer rotation crops. The short growing season of Maine does not appear to be very amenable to fall planting with most of the currently-available *Brassica* crops. From our work, it appears that for successful Brassica cover crops, fall plantings need to be made by the first week of August in Northern Maine and by mid-August in the rest of Maine to assure a productive cover crop. For use as a disease-suppressive green manure, even earlier plantings may be needed. Based on these results, the use of *Brassica* as a fall cover crop in Maine (and other areas with short growing seasons) may be extremely limited. Thus, under these conditions, inclusion of *Brassicas* in potato cropping systems in the northeast appears to be best used as a full-season, or early-season rotation crop or green manure. However, other crops, such as winter rye or ryegrass, can be successfully used as a cover crop later into the fall in Maine, with generally favorable results for the reduction of soilborne disease [26].

Although one specific rotation crop did not emerge as clearly better than others for reducing soilborne diseases in these trials, and results were somewhat variable from site to site, this does not necessarily suggest that the rotations were not effective at reducing disease. The results from the Newport site clearly demonstrated the increased disease pressure and low yields that occur when no rotation is used, as well as the substantial reductions in disease (by 14–58%) and improved yield (by 14–48%) that effective rotations can provide. At the other sites (which did not have continuous potato as a treatment), it was more difficult to distinguish among the rotations, in part because all the rotations used were fairly similar, and generally would be considered to be "good" rotations for use in potato production. Disease levels for black scurf, powdery scab, and silver scurf were generally lower than would be expected for these fields, possibly due to the rotation crops. Common scab, however, was present at moderate-substantial levels at all sites, and appeared to be less affected by the rotations (lower disease reductions) than other diseases. The variability in disease reduction that was observed at the different sites and years are likely due to a variety of interactions among numerous abiotic factors, such as soil properties, moisture, and temperature, and biotic factors, such as pathogen inoculum, crop dynamics, soil microbial community characteristics and fluctuations, that were occurring at each site, sub-site, and micro-site during the individual growing year. It is common for there to be much variability in the occurrence and development of soilborne diseases, in general, and for disease control, in particular. This variability accurately represents the reality and challenges associated with real-life on-farm disease management applications. Additionally, because the sites were located on different commercial farms and a research farm, the rotations were exposed to varying management practices, such as tillage and fertilization histories. In a survey summarizing the results from over 70 individual field trial interactions consisting of several different *Brassica* crops and rotations and under a variety of methodologies, conditions and locations, overall Brassica rotations and green manures were effective in increasing potato yield in over 50% of the trials, and effective in reducing black scurf disease in 70% of the trials, common scab in 40%, and powdery scab in 46% of the trials where those diseases occurred [20]. Thus, despite variability from trial to trial, overall results showed consistent benefits.

In this research, as well as in previous studies [15], *Brassica* crops were observed to reduce various soilborne diseases, and in some cases, the high-GSL *Brassica* crops (mustard blend, oriental, and Indian mustard) were the most effective of the *Brassicas*. However, in both these research studies, particular *Brassica* crops were never clearly superior to some other *Brassica* crops or to other non-*Brassica* rotations, producing generally comparable disease reduction. Thus, although a variety of *Brassica* crops do appear to offer potential for disease reduction and make positive contributions to the potato rotations, there is no clear evidence from these studies that *Brassica* rotation crops are significantly better than certain other rotation crops that also provide good disease control and crop benefits, such as perennial ryegrass.

5. Conclusions

Overall, results from these field trials indicate that the use of several different *Brassica* crops as well as selected non-*Brassica* crops as a single-year rotation crop (in two-year potato rotations), whether grown as a harvested crop or a green manure, can provide significant reductions in multiple soilborne potato diseases, including black scurf, common scab, and powdery scab (with best overall results observed with perennial ryegrass and a high-GSL mustard blend). However, reductions of specific diseases were not consistent over space and time, tuber yield was not substantially affected, and no single rotation crop was observed to be significantly better than several others. In addition, under the short growing season conditions of the Northeast U.S., *Brassica* crops were not successful as fall cover crops and are best used as full season rotation crops. It appears that factors other than relative glucosinolate content of *Brassica* crops are important in determining efficacy in reducing soilborne diseases, and potentially may be related to changes to the soil microbial communities. The variability observed in disease-reduction capabilities demonstrates the complex interactions that exist among rotation crops, host plants, pathogens, soil microbial communities, and various environmental parameters.

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