Plant Soil (2014) 374:611–627
DOI 10.1007/s11104-013-1909-4

REGULAR ARTICLE

Rapeseed rotation, compost and biocontrol amendments reduce soilborne diseases and increase tuber yield in organic and conventional potato production systems

Edward Bernard · Robert P. Larkin · Stellos Tavantzis · M. Susan Erich · Andrei Alyokhin · Serena D. Gross

Received: 24 April 2013 / Accepted: 6 September 2013 / Published online: 24 September 2013

Abstract
Aims Integrating multiple soil and disease management practices may improve crop productivity and disease control, but potential interactions and limitations need to be determined.
Methods Three different potential disease-suppressive management practices, including a *Brassica napus* (rapeseed) green manure rotation crop, conifer-based compost amendment, and three biological control organisms (*Trichoderma virens, Bacillus subtilis*, and *Rhizoctonia solani* hypovirulent isolate *Rhs1A1*) were evaluated alone and in combination at sites with both organic and conventional management histories for their effects on soilborne diseases and tuber yield.
Results Rapeseed rotation reduced all observed soilborne diseases (stem canker, black scurf, common scab, and silver scurf) by 10 to 52 % in at least one year at both sites. Compost amendment had variable effects on tuber diseases, but consistently increased yield (by 9 to 15 %) at both sites. Biocontrol effects on disease varied, though *Rhs1A1* decreased black scurf at the conventional site and *T. virens* reduced multiple diseases at the organic site in at least one year. Combining rapeseed rotation with compost amendment both reduced disease and increased yield, whereas biocontrol additions produced only marginal additive effects.
Conclusions Use of these treatments alone, and in combination, can be effective at reducing disease and increasing yield under both conventional and organic production practices.

Keywords Biocontrol · Compost amendment · Disease-suppressive · Disease management · Potato production · *Rhizoctonia solani* · Brassica rotation

Responsible Editor: Hans Lambers.

E. Bernard · S. Tavantzis · A. Alyokhin
School of Biology and Ecology, University of Maine,
Orono, ME 04469, USA

R. P. Larkin (✉)
USDA-ARS, New England Plant,
Soil and Water Laboratory,
Orono, ME 04469, USA
e-mail: Bob.Larkin@ars.usda.gov

M. S. Erich
Department of Plant, Soil, and Environmental Sciences,
University of Maine,
Orono, ME 04469, USA

S. D. Gross
Purdue University,
West Lafayette, IN 47907, USA

Introduction

Potato (*Solanum tuberosum* L.) growers face many challenges from seed- and soilborne pathogens, including reduced plant growth and vigor, as well as losses in tuber quality and total and marketable yield. The plant pathogens *Rhizoctonia solani* Kühn, *Helminthosporium solani* Durieu & Mont., and *Streptomyces scabiei* (ex. Thaxter) Lambert & Loria cause the economically important diseases stem canker and black scurf, silver scurf, and common scab, respectively. Short rotation lengths in many potato production systems exacerbate the problems caused by these diseases (Errampalli et al. 2001; Specht and Leach 1987; Wharton et al. 2007) but specific crop rotations and organic matter amendments provide control of many plant pathogens (Cohen et al. 2005; Kirkegaard and Sarwar 1998; Larkin 2008; Larkin and Honeycutt 2006).

Brassicaceous species, in particular, have profound effects on seed- and soilborne diseases of potato (Cohen et al. 2005; Larkin and Griffin 2007; Larkin et al. 2010; Larkin and Honeycutt 2006; Larkin et al. 2011a; Larkin et al. 2011b; Lazarovits 2010). Brassicaceous plants are known to produce glucosinolates, which break down to produce volatile compounds that are toxic to many plant pathogens, through a process known as biofumigation (Matthiesen and Kirkegaard 2006; Sarwar et al. 1998). The adoption of a canola or green manure rotation crop has been associated with significant decreases in severity and incidence of black scurf and stem canker (Larkin and Griffin 2007; Larkin et al. 2010; Larkin and Honeycutt 2006), as well as common scab (Larkin and Griffin 2007; Larkin et al. 2010). Other brassicaceous species, including oriental mustard (*Brassica juncea*) and rapeseed (*B. napus* 'Dwarf Essex') reduce black scurf and stem canker (Larkin and Griffin 2007; Larkin et al. 2010). Increases in tuber yield associated with brassicaceous crops have been inconsistent, despite the beneficial disease suppressive effects (Campiglia et al. 2009; Larkin and Griffin 2007; Larkin et al. 2010), which is comparable to the effects of other rotation crops on tuber yields in potato production systems (Carter et al. 2003; Davis et al. 1996).

Organic matter amendments such as composts may also provide control of some soilborne diseases (Bonanomi et al. 2010; Hoitink and Boehm 1999; Larkin et al. 2011b; Liu et al. 2007), though these effects may be more variable than results observed with rotation crops (Bonanomi et al. 2010; Termorshiuzen et al. 2007). Suppression of black scurf of potato has been reported with composted cow manure (Tsror et al. 2001) and suppression of other *R. solani* diseases has been reported with green wastes and composted cow manures in other systems (Noble and Coventry 2005; Pane et al. 2011). Al-Mughrabi et al. (2008) reported that various compost tea drenches and foliar applications reduced the severity of both silver scurf and black scurf in potato. Larkin et al. (2011a) reported a reduction in stem and stolon canker in a management system incorporating compost when compared to the continuous potato control, but black scurf and common scab were comparable between the control and the system incorporating compost. Tuber yield was, however, increased in the system incorporating compost (Larkin et al. 2011a). While this previous study utilized composts derived from dairy manures (Larkin et al. 2011a), a novel mechanism of suppression of rhizoctonia disease in potato is also associated with conifer-bark based composts. When conifer bark breaks down it releases quinic acid (Boudet 1973), which induces hypovirulence (the attenuation of disease-producing capability) in virulent isolates of *R. solani* (Liu et al. 2003). Larkin and Tavantzis (2013) have demonstrated reductions in stem canker and increases in tuber yield with the usage of a conifer-based compost.

Several biological control organisms have shown potential in reducing plant diseases (Asaka and Shoda 1996; Bénítez et al. 2004; Lewis and Papavizas 1987). Several species belonging to the genus *Trichoderma* are capable of parasitizing fungal plant pathogens such as *R. solani,* producing antibiotics effective against soilborne pathogens and competing for infection sites against pathogens (Bénítez et al. 2004; Vinale et al. 2008). *Trichoderma virens* and *T. harzianum* have been shown to be effective at controlling stem canker and black scurf, as well as increasing tuber yield (Brewer and Larkin 2005; Tsror et al. 2001; Wilson et al. 2008a; Wilson et al. 2008b). Kurzawińska (2006) also demonstrated an antagonistic effect of several *Trichoderma* species on *H. solani*, providing evidence for the potential suppression of silver scurf by *Trichoderma*. The bacterium *Bacillus subtilis* has disease-suppressive activity against some plant pathogens. The production of antibiotics by *B. subtilis* is effective at controlling tomato damping off, which is caused by *R. solani* (Asaka and Shoda 1996). Control of black scurf and stem canker by *B. subtilis* have been previously reported (Brewer and Larkin 2005; Larkin 2008; Larkin and Tavantzis 2013), as well as increases in tuber yield (Larkin and Brewer 2005). Other species of *Bacillus* have exhibited antagonistic activity against common scab (Han et al. 2005) and silver scurf (Martinez et al. 2002). Non-pathogenic isolates of of *R. solani* have demonstrated potential as biological control agents (Tsror et al. 2001; Bandy and Tavantzis 1990), including a naturally occurring hypovirulent isolate known as *Rhs1A1*. *Rhs1A1* reduced black scurf and stem canker of potato when applied in field experiments (Bandy and Tavantzis 1990; Larkin and Tavantzis 2013). It was also reported to increase dry weight of stem and stolons in a previous study (Bandy and Tavantzis 1990), though direct effects on tuber yield have not been observed (Larkin and Tavantzis, 2013).

In this study, we evaluated three different disease management approaches, compost amendment, biocontrol organisms, and a disease-suppressive rotation, for their individual and combined effects on soilborne diseases, as well as total and marketable tuber yield. Although many reports exist on the effects of some of the individual treatments incorporated in this study on disease and/or yield, there are few, if any, that report on the systematic and combined effects of more than one type of management practice and on more than a single disease. Furthermore, some of the treatments employed here have not been investigated for their effects on disease and yield in a practical agricultural setting (conifer-based compost, *Rhs1A1*). These practices were utilized at two sites with different management histories. One site has a long history of conventional production practices, whereas the other site has a history of sustainable (organic matter-conserving) organic production practices. Previous research has typically focused on sites with conventional management histories, and occasionally with organic histories, but rarely both.

The main objectives of the work reported here were to evaluate a rapeseed green manure rotation, a conifer-based compost amendment and biocontrol organisms for their: (i) individual and combined treatment effects on soilborne diseases of potato; (ii) individual and combined treatment effects on total and marketable yield of tubers; and (iii) whether these effects differed at an organically-managed potato production site compared with a conventional potato production site. This research is part of a larger project, in which these management practices were also assessed for their effects on soil physical and chemical properties (Erich et al., unpublished data), insect pests (Gross 2010), and soil microbial community characteristics (Bernard et al. 2012).

Materials and methods

Field Sites Field trials were conducted during 2007–2009 at two sites in northern Maine. The sites were Wood Prairie Farm (WPF) a commercial, organic farm in Bridgewater, Maine that has been using organic production and management practices for 35 years, and Aroostook Research Farm (AF) a University of Maine Agriculture and Forestry Experiment Station farm located 35 km north of WPF in Presque Isle, Maine, that has a history (decades) of conventional potato production practices. Soil type at WPF was a Mapleton loam (fine-loamy, mixed superactive, frigid, Dystric Eutrudepts) and soil type at AF was a Caribou gravelly loam (fine-loamy, isotic, frigid, Typic Haplorthods). Soil physical characteristics (texture) were similar at both sites, but chemical characteristics were notably different, with much higher total C, N, and Ca content at WPF due to its long history of organic amendments and sustainable management practices (Bernard et al. 2012). Field trials were incorporated into the existing potato rotations already in place at each farm. At AF, this consisted of a standard 2-year rotation of barley followed by potato, which is fairly typical of conventional potato production in this region. At WPF, the rotation used was a 4-year rotation consisting of oats (underseeded with timothy and clover), a full year of clover, then plowdown buckwheat (green manure) with an additional fall green manure crop of rapeseed, followed by potato in the fourth year.

Treatments There were three treatment factors: compost, biocontrol organisms (three), and a preceding rapeseed green manure crop. The compost used (Cobscook Blend; Coast of Maine Organic Products, Inc., Portland, Maine) consisted of hemlock bark, salmon and blueberry waste products from commercial processing operations, cow manure, sphagnum peat, and limestone, and was matured for 9–12 months before use and was rated as very stable using Dewar self-heating (Brinton et al. 1995). Compost was applied by hand at a rate of 20 tons per hectare in the furrow at planting. Analysis of the compost has been described previously (Bernard et al. 2012). The three biocontrol organisms used were *Bacillus subtilis* (Kodiak®, Bayer CropScience LP, Research Triangle Park, North Carolina), *Trichoderma virens* (SoilGard®, Certis USA, Columbia, MD), and a hypovirulent strain of *R. solani* (*Rhs1A1* (Jian et al. 1997) maintained at the

University of Maine, Orono, Maine). All biological control organisms were applied in furrow at the time of planting. *B. subtilis* was applied as a 2 % suspension (2 g/L) at a rate of 300 ml/row. *T. virens* was used as a granular application at a rate of 75 g/row. Hypovirulent *R. solani* (*Rhs1A1*) was grown for three weeks on cracked wheat and applied at a rate of 150 g/row (Bernard et al. 2012). The green manure rotation crop of rapeseed (cultivar 'Dwarf Essex') was grown for approximately 2 months in the fall (August–September), then the fresh biomass incorporated into the soil (around October). The non-rapeseed treatment consisted of the standard rotation crop prior to potato for that site, which was barley at AF and spring-planted buckwheat green manure without fall rapeseed green manure at WPF.

Experimental set-up and design Research plots were initially established in 2007 at each site in a randomized split-block design, with compost amendment as the main factor and biocontrol organism as the split factor, with four replicate plots for each treatment. Individual plots were 7.6 m long by 5.5 m wide and consisted of six rows of potatoes with 0.9 m between rows. Soil amendments (compost and biocontrol organisms) were only applied to the central four rows of each plot. Thus, in 2007, there were a total of 32 plots (2 compost treatments (amended and nonamended) × 4 biocontrol treatments (three organisms and nonamended) × 4 replicate plots). Since these trials followed the standard rotation sequence at each site, plots established in subsequent years were necessarily new plots in a different location within each farm, in an adjacent or nearby field that was scheduled to be planted to potatoes that year. Thus, there were no residual effects from the previous year, and each year represented a separate trial at each site. In the 2008 and 2009 trials, the presence or absence of rapeseed grown as a fall green manure crop was added to the study as an additional factor (a preceding crop rotation could not be incorporated into the design in the first year of the study). Plot sizes and all other parameters were the same in 2008 and 2009, but the experiment was twice the size as that of 2007, with experimental design now a split-split block, consisting of 64 plots (2 rotation treatments × 2 compost treatments x 4 biocontrol treatments × 4 replicate plots).

In all years, potatoes (cv. 'Yukon Gold') were planted using a machine planter with spacing approximately 17 cm apart. Planting occurred May 31st, 2007, June 5th, 2008, and June 4th, 2009 at AF, and on June 1st, 2007, June 3rd, 2008, and June 3rd, 2009 at WPF. Fertilization regimes and pesticide applications followed the standard practices for each farm (Bernard et al. 2012). Plant emergence (%) at 3 weeks after planting was determined for all plots in 2007 and 2008 only.

Disease assessments and tuber harvest In mid-August, stem and root samples were destructively harvested from four whole plants arbitrarily selected in rows 2 and 5 of each plot for assessment of stem and stolon canker. Roots and stolons were then visually inspected for canker lesions and rated separately on a 0–5 rating scale (Brewer and Larkin 2005) for stem and stolon canker.

All tubers from the middle two rows of each plot (15.2 m total row length) were harvested on Sept. 12, 2007, August 24, 2008 and September 23, 2009 at Aroostook Farm, and September 14, 2007, September 22, 2008, and September 11, 2009 at Wood Prairie Farm, and total weight determined. All harvested tubers were then graded into size classes (corresponding to small, medium, large and extra-large sizes) and marketable yield was calculated as the total weights of the three larger size classes. A subsample of 40 harvested tubers per plot were arbitrarily selected and rated for incidence and severity of black scurf, common scab, and silver scurf. Severity was determined as the percentage of the tuber surface affected by disease. The incidence of substantial disease was calculated as the percentage of tubers above a threshold disease rating, which was greater than 2 % severity for the individual diseases (black scurf, common scab, and silver scurf) and 5 % severity for the total incidence of all diseases combined. These thresholds indicate disease levels above which these diseases are particular problems for seed and fresh market usage, and thus provide a more useful indicator for growers.

Data analyses Soilborne disease and tuber yield data were analyzed by analysis of variance (ANOVA) with factorial treatment structure and interactions (split-block design). Data from each potato crop year were analyzed individually. Significance was evaluated at $P<0.05$ for all tests. Mean separation was carried out with Fisher's protected least significant difference test.

All analyses were conducted using Statistical Analysis Systems version 9.2 (SAS Institute, Cary, NC), with the general linear models procedure used for all ANOVA analyses.

Results

Environmental conditions Average weather conditions for the three growing seasons (2007 to 2009) were fairly typical for each location, with 2007 being somewhat drier, and 2008 wetter than the long-term (30-year) average conditions (Table 1). In 2009, although total rainfall for the summer was close to average, much wetter than normal conditions existed throughout June and July (particularly at Bridgewater, where July rainfall was nearly double the average amount) (Table 1). The Bridgewater location (WPF) also averaged higher summer rainfall than Presque Isle (AF), ranging from 6.1 to 8.2 cm more rain per summer over the three years. Average summer air temperatures were consistent from year to year, and comparable to the long-term averages at each site (Table 1). Bridgewater averaged slightly cooler temperatures than Presque Isle.

Crop and disease development The potato crops developed relatively uniformly across all treatments in all years. Overall, there were no significant differences among treatments for percent emergence at either site in either year, though emergence was substantially earlier in 2007 (55 % to 66 % at AF; 89 % to 92 % at WPF) than 2008 (29 % to 32 % at AF; 47 % to 50 % at WPF). Emergence was also earlier at Wood Prairie Farm than at Aroostook Farm. Tuber yields were typical for this area and variety at both sites, with total overall yield ranging from 21 to 30 Mg/ha at AF and 24 to 28 Mg/ha at WPF (Figs. 1 & 2). The primary potato diseases observed in each of the three seasons at each site were stem and stolon canker, black scurf, common scab, and silver scurf. Rhizoctonia disease levels (canker and black scurf) were low to moderate at both farms with disease levels slightly higher for common scab and silver scurf.

Each of the three treatment factors (rapeseed rotation, compost amendment, and biocontrol amendment) significantly affected disease development in some or all of the assessment years at each location. For most

Table 1 Total rainfall and average daily temperature for the months May to September for 2007 to 2009 at Presque Isle (Aroostook Farm site) and Bridgewater, ME (Wood Prairie Farm site) compared with long-term (30-yr) average conditions

Location Month	Rainfall (cm)[a]				Average Daily Air Temperature (°C)[a]			
	2007	2008	2009	Long-term avg	2007	2008	2009	Long-term avg
Presque Isle								
May	6.9	6.3	11.3	8.7	11.3	10.8	11.7	11.4
June	6.3	13.1	11.7	8.6	17.2	16.6	16.4	16.4
July	10.6	8.2	12.6	9.4	19.2	21.0	18.3	19.0
August	10.6	11.9	5.7	10.0	17.7	18.4	19.7	18.2
September	5.0	8.6	3.4	8.7	14.7	14.2	14.0	13.2
Total	39.4	48.1	44.7	45.4	80.1	81.0	80.1	78.2
Bridgewater								
May	5.8	7.4	10.4	9.2	10.9	10.2	11.1	11.1
June	8.4	13.6	13.1	9.3	16.5	16.2	15.9	16.2
July	8.7	10.5	18.5	9.9	18.4	20.2	18.0	18.8
August	10.5	10.2	4.9	10.1	17.1	17.7	19.2	17.9
September	3.6	12.5	5.4	9.1	14.2	13.5	12.6	13.1
Total	37.0	54.2	52.4	47.6	77.1	77.8	76.8	77.1

[a] Rainfall and temperature estimates were compiled from NOAA National Climatic Data Center local monitoring information for Presque Isle and Bridgewater, ME, respectively

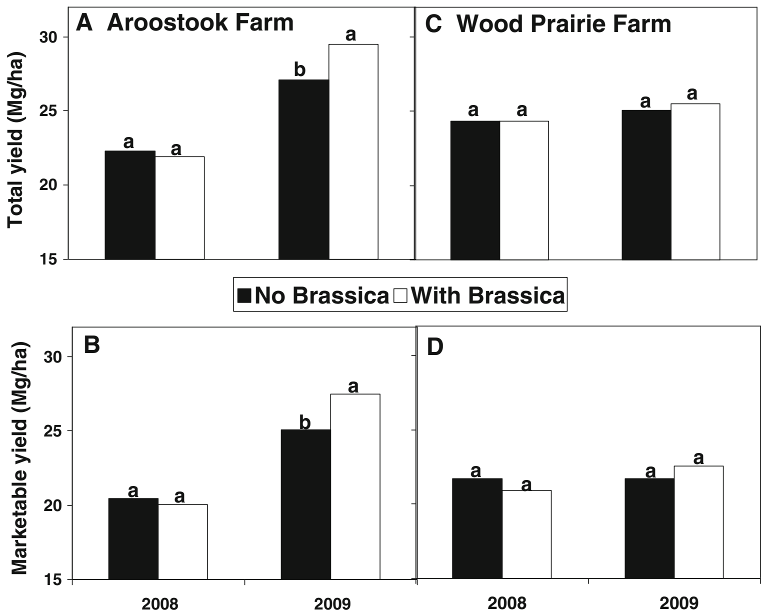

Fig. 1 Total and marketable tuber yield as affected by the presence or absence of a *Brassica* green manure (rapeseed) crop prior to planting to potato at Aroostook Farm (**a**, **b**) and Wood Prairie Farm (**c**, **d**) in 2008 and 2009. Bars within years topped by the same letter are not significantly different based on analysis of variance (P>0.05)

years and parameters, interactions among the treatment factors were not significant, or were minor in comparison to the main effects. However, in a few cases (particularly rotation × compost amendment effects on soilborne diseases in the 2008 season) there were significant treatment interactions (Table 2). Significant treatment interactions were not observed for any yield parameters, or on disease parameters in 2007 and, with very few specific exceptions, in 2009. These results indicate that the main factor effects were similar across the different treatment combinations. Each factor will be addressed separately in the following sections. The consequences of specific treatment interactions will also be addressed subsequently.

Rapeseed rotation effects on disease development Rapeseed rotation reduced the severity and incidence of all observed tuber diseases in at least one year at each site. The incidence and severity of black scurf, common scab, silver scurf, and total tuber diseases

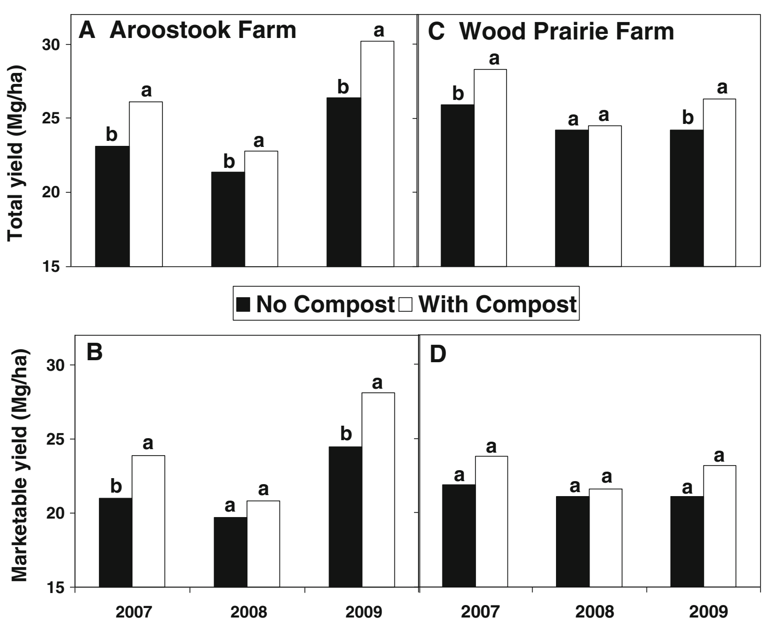

Fig. 2 Total and marketable tuber yield as affected by the presence or absence of a compost amendment at Aroostook Farm (**a**, **b**) and Wood Prairie Farm (**c**, **d**) in 2008 and 2009. *Bars* within years topped by the same letter are not significantly different based on analysis of variance (P>0.05)

Table 2 ANOVA table showing *p* values (probability of non-significant effects) for the main treatment factors, rapeseed rotation (Rot), compost amendment (Comp) and biological control organism (Bc), and their interactions on soilborne diseases including black scurf, common scab and silver scurf in 2008 at Aroostook and Wood Prairie Farm sites

Site Factor[a]	BS[b] Sev	BS Inc	CS[b] Sev	CS Inc	SS[b] Sev	SS Inc	Tot Sev	Tot Inc
Aroostook Farm								
Rotation (Rot)	0.0635	0.0378	0.0083	0.0106	0.0062	0.0065	0.0059	0.0011
Compost (Comp)	0.0180	0.0183	0.0016	0.0008	0.0258	0.0132	0.0021	0.0016
Biocontrol (Bc)	0.1487	0.1815	0.1199	0.6476	0.2555	0.5725	0.3811	0.2134
Rot*Comp	0.0003	0.0005	0.0005	<0.0001	0.0228	0.2525	<0.0001	0.0002
Rot*Bc	0.2974	0.3208	0.2376	0.0705	0.4670	0.3230	0.5367	0.5249
Comp*Bc	0.8653	0.8875	0.2902	0.1802	0.9348	0.5188	0.6595	0.7919
Rot*Comp*Bc	0.7767	0.6515	0.2204	0.4371	0.1537	0.5011	0.2304	0.2431
Wood Prairie Farm								
Rot	0.0169	0.2610	0.0657	0.1091	0.0121	0.0029	0.0191	0.0340
Comp	0.0075	0.9378	0.6737	0.8209	0.5325	0.8417	0.3416	0.2166
Bc	0.4609	0.2403	0.1763	0.2387	0.0153	0.0053	0.0643	0.1711
Rot*Comp	0.1860	0.9063	0.0006	<0.0001	0.0926	0.0026	0.0048	0.0028
Rot*Bc	0.0501	0.0167	0.8882	0.6635	0.2600	0.7884	0.6688	0.7014
Comp*Bc	0.0639	0.0828	0.9046	0.9368	0.6263	0.4506	0.7198	0.6231
Rot*Comp*Bc	0.0088	0.0090	0.0520	0.4631	0.9209	0.9355	0.0690	0.0771

[a] Factors were analyzed taking into account the split-block design.

[b] *BS* black scurf, *CS* common scab, *SS* silver scurf, and *Tot* Total (for all tuber diseases). *Sev* Severity, which refers to the percentage of the tuber surface area damaged or affected by the disease. *Inc* Incidence, which refers to the incidence of tubers with substantial disease, represented by the percentage of tubers with a severity rating of 2 % or greater for that disease

were significantly decreased in plots following rapeseed rotation compared to plots following the standard rotation in both years (2008 and 2009) at WPF, and in 2008 only at AF (Table 3). Overall, the addition of the rapeseed rotation reduced the severity and incidence of all tuber diseases together by 26 % and 53 %, respectively, at AF in 2008, by 23 % and 46 % at WPF in 2008, and by 17 % and 28 % at WPF in 2009 (Table 3). Rapeseed rotation also significantly decreased the development of stolon canker at AF in 2008 (0.92 vs. 1.14 rating, p=0.003), though not in any other year or at WPF. Stem canker was not affected by rapeseed rotation at either site in any year (data not shown).

Effect of compost amendment on disease development Compost amendment resulted in significant reductions in the incidence and severity of black scurf at AF in 2007 relative to nonamended plots, with reductions averaging 12 % and 27 % for severity and incidence, respectively (Table 4). However, this trend was reversed in subsequent years, when compost amendment resulted in significantly higher severity of black scurf at AF in 2008 and 2009, as well as higher severity and incidence of common scab in 2007 and 2008, and higher incidence and severity of silver scurf in 2008 and 2009 (Table 4). At AF, stem canker severity was increased with compost amendment in both 2007 (1.63 vs. 1.46, p=0.04) and 2008 (1.97 vs. 1.75, p=0.02), while stolon canker was significantly increased with compost amendment in 2008 only (1.09 vs. 0.96, p=0.03). Although there were no significant effects of compost amendment in 2007 at WPF, black scurf severity was higher in composted plots in 2008 and 2009, and common scab and silver scurf also increased with compost amendment in 2009 (Table 4), while there were no significant effects on stem and stolon canker (data not shown). Overall, addition of compost amendment resulted in total tuber disease increases in severity and incidence by 13 % to 80 % at AF, and by 5 % to 28 % at WPF in 2008 and 2009.

Biocontrol effects on disease development Biocontrol treatments had some significant effects on the incidence and severity of tuber diseases at both sites and

Table 3 Effect of Brassica (rapeseed) green manure prior to potato as part of rotation sequence on the incidence and severity (% surface area coverage) of soilborne tuber diseases (black scurf, common scab, silver scurf, and total of all three) at Aroostook and Wood Prairie Farm sites in 2008 and 2009

Site Year Treatment	Black scurf		Common scab		Silver scurf		Total disease	
	Severity[a]	Incidence[b]	Severity	Incidence	Severity	Incidence	Severity	Incidence
Aroostook Farm								
2008								
No Brassica	1.06 a[d]	25.1 a	1.86 a	66.7 a	1.75 a	60.5a	4.68 a	56.0 a
With Brassica	0.92 b	20.6 b	1.51 b	46.9 b	1.02 b	29.0 b	3.45 b	26.5 b
2009								
No Brassica	0.69 a	10.4 a	1.58 a	50.4 a	1.70 a	59.4 a	3.98 a	40.0 a
With Brassica	0.67 a	6.9 b	1.53 a	47.6 a	1.78 a	60.1 a	3.99 a	38.2 a
Wood Prairie Farm								
2008								
No Brassica	0.73 a	15.6 a	1.91 a	66.9 a	2.24 a	76.4 a	4.88 a	56.5 a
With Brassica	0.54 b	11.4 b	1.48 b	46.3 b	1.71 b	53.0 b	3.74 b	30.7 b
2009								
No Brassica	0.71 a	4.5 a	1.29 a	31.7 a	1.79 a	66.3 a	3.80 a	34.2 a
With Brassica	0.44 b	2.6 a	1.07 b	20.5 b	1.64 b	50.5 b	3.14 b	24.5 b

[a] Severity refers to the percentage of the tuber surface area damaged or affected by the disease

[b] Incidence refers here to the incidence of tubers with substantial disease, and is determined by the percentage of tubers with a severity rating of 2 % or greater for that disease

[c] Total disease severity refers to the average combined surface area coverage of all tuber diseases

[d] Total disease incidence refers to the percentage of tubers with a total disease severity of 5 % or greater

[e] Means within columns for each location and within years followed by the same letter are not significantly different according to Fisher's protected LSD test at $P=0.05$

in all years. However, effects were relatively small and inconsistent between sites and from year to year. Black scurf severity and incidence were significantly lower in *Rhs1A1* amended plots than in nontreated plots and plots receiving *B. subtilis* amendments in 2007 at AF, and was lower than plots receiving *B. subtilis* amendments in 2008 (Table 5). These amounted to reductions of 20 % to 23 % in severity and 30 % to 36 % in incidence. However, at WPF, *T. virens* plots had significantly lower black scurf incidence and severity than control and *Rhs1A1* plots in 2007, representing reductions of 15 % to 47 %. *Rhs1A1* and *B. subtilis* also reduced severity of stem canker relative to control plots (1.55 and 1.38 vs. 1.81, $p=0.02$), and *T. virens* reduced stolon canker (1.41 vs. 1.70, $p=0.05$) at AF in 2007. At WPF in 2007, *B. subtilis* also reduced severity of stolon canker relative to *T. virens* and control plots (1.37 vs. 1.67, $p=0.04$). None of the biological control amendments reduced rhizoctonia diseases (black scurf, stem or stolon canker) at WPF in 2008 and 2009 (Table 5).

Plots amended with *T. virens* resulted in significantly lower severity of common scab than plots amended with *B. subtilis* and *Rhs1A1*, as well as lower incidence than the *B. subtilis* and control plots at AF in 2007. Common scab severity and incidence was also reduced in plots amended with *Rhs1A1* and *T. virens* relative to control plots at AF in 2009 (Table 6). At WPF, significantly lower incidence of common scab was observed in *Rhs1A1* plots than control plots in 2007, and lower incidence and severity in both *Rhs1A1* and *T. virens* plots than control plots in 2009, representing reductions in incidence of 10 % to 32 % (Table 6).

Overall, incidence and severity of silver scurf was generally not significantly affected by biocontrol treatments at AF, but was somewhat affected by biocontrol at WPF in 2007 and 2008. Severity was significantly decreased in plots amended with *T. virens* relative to control plots in 2007 at WPF, whereas *Rhs1A1* significantly decreased both incidence and severity of silver

Table 4 Effects of compost amendment on the incidence and severity (% surface area coverage) of soilborne tuber diseases (black scurf, common scab, silver scurf, and total of all three) at Aroostook Farm and Wood Prairie Farm in all three years

Site Year Treatment	Black scurf		Common scab		Silver scurf		Total disease	
	Severity[a]	Incidence[b]	Severity	Incidence	Severity	Incidence	Severity	Incidence
Aroostook Farm								
2007								
No Compost	1.16 a[e]	31.4 a	1.77 b	61.9 b	1.72 a	56.4 a	4.65 a	53.8 a
With Compost	1.02 b	22.8 b	1.95 a	73.3 a	1.74 a	59.1 a	4.71 a	57.2 a
2008								
No Compost	0.75 b	14.1 b	1.53 b	48.6 b	1.22 b	37.8 b	3.50 b	29.0 b
With Compost	1.23 a	30.7 a	1.84 a	65.1 a	1.55 a	51.7 a	4.62 a	53.6 a
2009								
No Compost	0.63 b	8.6 a	1.53 a	47.7 a	1.59 b	52.6 b	3.75 b	36.3 b
With Compost	0.73 a	8.6 a	1.59 a	50.3 a	1.90 a	67.0 a	4.22 a	42.0 a
Wood Prairie Farm								
2007								
No Compost	0.94 a	11.9 a	1.77 a	64.4 a	1.54 a	44.1 a	4.29 a	41.4 a
With Compost	0.90 a	12.8 a	1.82 a	67.0 a	1.50 a	41.6 a	4.22 a	40.8 a
2008								
No Compost	0.58 b	13.4 a	1.67 b	55.9 a	1.95 a	64.3 a	4.20 b	39.7 b
With Compost	0.70 a	13.5 a	1.73 a	57.3 a	2.00 a	65.1 a	4.42 a	47.5 a
2009								
No Compost	0.48 b	3.3 a	1.14 b	22.8 b	1.58 b	51.4 b	3.20 b	25.8 b
With Compost	0.66 a	3.8 a	1.23 a	29.4 a	1.85 a	65.4 a	3.74 a	32.9 a

[a] Severity refers to the percentage of the tuber surface area damaged or affected by the disease

[b] Incidence refers here to the incidence of tubers with substantial disease, and is determined by the percentage of tubers with a severity rating of 2 % or greater for that disease

[c] Total disease severity refers to the average combined surface area coverage of all tuber diseases

[d] Total disease incidence refers to the percentage of tubers with a total disease severity of 5 % or greater

[e] Means within columns for each location and within years followed by the same letter are not significantly different according to Fisher's protected LSD test at P=0.05

scurf in 2008 at WPF (Table 7). Incidence of silver scurf was also significantly lower in plots amended with *B. subtilis* relative to control plots in 2007, representing a 20 % decrease (Table 7).

Treatment effects on tuber yield Rapeseed rotation had no significant effect on total or marketable tuber yield at AF in 2008 or WPF in either year (Fig. 1). However, presence of the rapeseed rotation significantly increased both total and marketable tuber yield at AF in 2009, resulting in yield increases of 9 % to 10 % (Fig. 1), with marketable yield representing the combined weights of the three largest size classes of tubers. Compost amendment resulted in higher total and marketable tuber yields in 2007 and 2009 at both sites relative to nonamended control plots, with yield increases of 13 % to 15 % at AF and 9 % to 10 % at WPF (Fig. 2). In 2008, total yield was higher (7 %) with compost amendment at AF. Much of the increased yield due to compost amendment was apparently due to an increase in the larger tuber size classes, as the weight of the large and extra large size classes, as well as the percentage of tubers in those classes increased at both sites in most years. For example, the weight of extra large tubers increased by 47 % to 85 % at WPF and by 45 % to 77 % at AF relative to nonamended plots over all three years (p=0.01–0.04). Moreover, the total weight of large and extra large tubers was increased by

Table 5 Effect of biocontrol treatments on the incidence and severity (% surface area coverage) of black scurf on potato tubers at Aroostook and Wood Prairie Farm sites in 2007, 2008, and 2009

Site Treatment	2007		2008		2009	
	Severity[a]	Incidence[b]	Severity[a]	Incidence[b]	Severity[a]	Incidence[b]
Aroostook Farm						
No biocontrol	1.18 a[c]	29.4 a	0.98 ab	22.2 ab	0.61 b	6.4 b
B. subtilis	1.19 a	31.9 a	1.12 a	27.3 a	0.74 a	11.1 a
T. virens	1.07 ab	26.9 ab	0.96 ab	21.4 ab	0.67 ab	8.3 ab
Rhs1A1	0.91 b	20.3 b	0.89 b	18.5 b	0.71 ab	8.3 ab
Wood Prairie Farm						
No biocontrol	0.98 a	14.4 a	0.64 a	12.3 a	0.57 a	3.4 a
B. subtilis	0.88 ab	10.6 ab	0.70 a	16.6 a	0.57 a	2.9 a
T. virens	0.83 b	8.4 b	0.62 a	11.9 a	0.58 a	2.5 a
Rhs1A1	0.99 a	15.9 a	0.61 a	13.3 a	0.57 a	5.3 a

[a] Severity refers to the percentage of the tuber surface area damaged or affected by the disease

[b] Incidence refers here to the incidence of tubers with substantial disease, and is determined by the percentage of tubers with a severity rating of 2 % or greater for that disease

[c] Means within columns for each location followed by the same letter are not statistically different according to Fisher's protected LSD test at $P=0.05$

13 % to 24 % at AF with compost amendment over all three years, and by 13 % to 22 % at WPF in 2008 and 2009 when compared to nonamended control plots. Biocontrol amendments generally had no significant or consistent effects on total, marketable, or individual size class yields at either site, except at AF in 2008 where total and marketable yield were significantly lower in plots amended with *Rhs1A1* compared to nonamended plots (data not shown).

Treatment interactions and combinations Overall, there were few occurrences of significant treatment

Table 6 Effect of biocontrol treatments on the incidence and severity (% surface area coverage) of common scab on potato tubers at Aroostook and Wood Prairie Farm sites in 2007, 2008, and 2009

Common scab	2007		2008		2009	
	Severity[a]	Incidence[b]	Severity[a]	Incidence[b]	Severity[a]	Incidence[b]
Aroostook farm						
No biocontrol	1.82 ab	70.0 a	1.64 a	57.5 a	1.25 a	46.3 a
B. subtilis	1.98 a	73.1 a	1.64 a	58.6 a	1.22 ab	52.1 a
T. virens	1.77 b	57.5 b	1.74 a	54.7 a	1.12 c	48.9 a
Rhs1A1	1.87 a	69.7 ab	1.74 a	56.6 a	1.15 bc	48.6 a
Wood Prairie Farm						
No biocontrol	1.85 a	72.2 a	1.68 a	55.5 a	1.25 a	31.1 a
B. subtilis	1.81 a	64.4 ab	1.73 a	57.6 a	1.22 ab	28.9 ab
T. virens	1.80 a	64.4 ab	1.74 a	59.4 a	1.12 c	21.1 c
Rhs1A1	1.72 a	61.9 b	1.64 a	53.9 a	1.15 bc	23.4 bc

[a] Severity refers to the percentage of the tuber surface area damaged or affected by the disease

[b] Incidence refers here to the incidence of tubers with substantial disease, and is determined by the percentage of tubers with a severity rating of 2 % or greater for that disease

Table 7 Effect of biocontrol treatments on the incidence and severity (% surface area coverage) of silver scurf on potato tubers at Aroostook and Wood Prairie Farm sites in 2007, 2008, and 2009

Silver scurf	2007		2008		2009	
	Severity[a]	Incidence[b]	Severity[a]	Incidence[b]	Severity[a]	Incidence[b]
Aroostook farm						
No biocontrol	1.75 a	58.8 a	1.43 a	46.3 a	1.74 a	59.8 a
B. subtilis	1.71 a	57.5 a	1.29 a	42.3 a	1.64 a	57.5 a
T. virens	1.69 a	55.3 a	1.36 a	43.9 a	1.77 a	59.6 a
Rhs1A1	1.78 a	59.4 a	1.45 a	46.5 a	1.77 a	62.3 a
Wood Prairie Farm						
No biocontrol	1.64 a	50.0 a	1.97 ab	65.3 a	1.73 a	60.8 a
B. subtilis	1.50 ab	39.7 b	1.97 ab	64.7 ab	1.67 a	57.5 a
T. virens	1.47 b	40.3 b	2.09 a	69.8 a	1.69 a	56.3 a
Rhs1A1	1.49 ab	41.4 ab	1.87 b	59.1 b	1.75 a	60.8 a

[a] Severity refers to the percentage of the tuber surface area damaged or affected by the disease

[b] Incidence refers here to the incidence of tubers with substantial disease, and is determined by the percentage of tubers with a severity rating of 2 % or greater for that disease

interactions throughout the course of this study, being restricted primarily to rotation × compost interactions for disease parameters in 2008 (Table 2). In addition, there was an isolated interaction between rotation and biocontrol, as well as rotation×compost×biocontrol for black scurf at WPF in 2008 (Table 2). There were no significant interactions for any factors regarding yield parameters at either site in any year, or disease parameters in 2007, or at AF in 2009. However, there were some specific interactions indicated at WPF in 2009, including significant rotation×biocontrol and compost×biocontrol interactions for black scurf, silver scurf, and total disease incidence and severity (p=0.007 to 0.0311). These interactions were characterized primarily by inconsistent biocontrol effects across the other factors, including examples where a biocontrol organism showed some effects with no compost amendment (or rapeseed rotation), but not with compost (or with rapeeed rotation). However, these relationships were transient and did not constitute consistent responses over the course of the study, but serve to illustrate why overall biocontrol effects were rarely significant.

The interactions observed between compost amendment and rapeseed rotation found in 2008 at both sites (Table 2) and also in 2009 at WPF, but only for silver scurf incidence (p=0.005) and total disease severity (p=0.036), serve to illustrate the combined effects of these two treatments as well as their interactions. In these combinations, plots receiving the rapeseed rotation with no compost generally had the lowest disease levels, whereas plots with no rapeseed rotation and with compost amendment generally had the highest disease levels, while other combinations fell somewhere in between (Table 8). In cases where there was no interaction, such as with silver scurf severity at AF in 2008, there were clear differences for each treatment combination, and a clear progression of combined effects (Table 8). However, when there was a significant interaction, such as with black scurf or common scab incidence at AF in 2008, the relationship did not follow the same pattern, due to these interacting effects (Table 8). Ultimately, in situations where there was a compost–by-rotation crop interaction, the reduction in disease severity provided by the rapeseed rotation crop generally compensated for the increase in severity associated with compost amendment.

Overall, the combination of compost amendment and rapeseed rotation generally resulted in the combined effects of reduced disease, due to rapeseed rotation, and increased yield, due to compost amendment (Table 8). Such combined effects are referred to as complementary, because each treatment contributes significant effects on different components, in this case disease reduction and yield increase, as opposed to additive effects, which generally refers to enhanced effects on the same parameter. For treatment

Table 8 Combined rapeseed and compost effects on incidence of potato tuber diseases and total yield in both years at both sites (AF = Aroostook Farm, WPF = Wood Prairie Farm)

Year Treatment	Black Scurf[a]		Common Scab[a]		Silver Scurf[a]		Total Yield	
	AF	WPF	AF	WPF	AF	WPF	AF	WPF
2008								
BRWC[b]	34.1 a[d]	11.3 a	60.2 b	51.6 c	37.4 c	56.7 b	23.2 a	25.5 a
BRNC[b]	7.2 c	11.4 a	33.8 c	41.1 d	20.6 d	49.4 c	20.7 b	23.2 a
NOWC[b]	27.2 ab	15.8 a	70.0 a	63.1 b	66.1 a	73.6 a	22.5 ab	23.6 a
NONC[b]	20.9 b	15.5 a	63.4 ab	70.6 a	55.0 b	79.2 a	22.2 ab	25.1 a
2009								
BRWC	7.6 a	2.7 a	48.0 a	23.8 b	65.5 a	60.2 b	31.1 a	26.8 a
BRNC	6.2 a	2.5 a	47.3 a	17.3 c	54.8 b	40.8 c	28.0 b	24.2 b
NOWC	9.7 a	5.0 a	52.5 a	35.2 a	68.6 a	70.6 a	29.4 ab	25.9 a
NONC	11.1 a	4.1 a	48.2 a	28.3 a	50.4 b	62.0 b	24.9 c	24.3 b

[a] Disease incidence refers to the percentage of tubers affected by the disease with a severity greater than 2 % surface coverage

[b] Represents the combination of rapeseed and compost treatments. *BR* With rapeseed, *NO* No rapeseed, *WC* With compost, *NC* No compost

[c] Means within columns for each year followed by the same letter are not statistically different according to Fisher's protected LSD test at *P*=0.05

combinations involving the biocontrol amendments with either rapeseed rotation or compost amendment, due to the rather small or variable effects of the biocontrol agents themselves, there were generally no significant effects due to addition of biocontrol organisms above those observed for rapeseed rotation or compost amendment alone (data not shown). However, there were some indications of enhanced combined effects, as compost and *Rhs1A1* were each found to provide an overall reduction in the incidence of black scurf at AF in 2007 (Tables 4 and 5), and their combination led to an incidence of 17.5 %, which was nominally lower than either treatment alone.

Discussion

This research represents three years of field data assessing the effects of multiple disease management approaches, specifically compost amendment, biological control organisms, and a rapeseed green manure rotation crop, on soilborne diseases and yield of potato. In terms of disease suppression, rapeseed rotation provided the broadest effect, reducing total and individual (black scurf, silver scurf, and common scab) disease incidence and severity at both sites, while producing significant effects on total and marketable tuber yield at one site. Compost amendment provided significant increases in total tuber yield in all three years at AF, and in 2007 and 2009 at WPF, but also resulted in increased disease in two of the three years of the study. The biocontrol amendment effects were less consistent, as significant effects on disease suppression were often observed in only a single year or at a single site, and none of the biocontrol amendments had consistent effects on tuber yield. Combinations of these treatments produced mixed results, with treatment interactions observed in some years (particularly rotation × compost amendment in 2008) and biocontrol additions showing no consistent effects when combined with other treatments, but the combination of rapeseed rotation and compost amendment generally resulted in the complementary effects of reduced tuber disease and increased yield.

Overall, many treatment effects were the same or similar at both sites, such as disease suppression by rapeseed rotation and increased yield with compost amendment, indicating that these treatments are effective even with varied background conditions and management histories. However, some effects were different between the two sites. WPF is an organic site characterized by yearly organic matter inputs and a four-year rotation which ordinarily includes a rapeseed cover crop compared to AF, which is a conventionally managed farm with a short, two-year rotation. One of the primary resulting differences between the sites is in the amount of organic matter and organic C in the soils, with WPF having more than double that of AF (Bernard et al. 2012). Another indication of the difference between sites was that while levels of disease severity were generally similar between AF and WPF, incidence was lower overall at WPF and is likely attributed to the history of disease suppressive management practices at WPF, which have included yearly applications of biological control organisms and organic matter amendments, and may be responsible for differential effects observed in the microbial community in response to soil amendments (Bernard et al. 2012).

Incorporation of the rapeseed rotation crop resulted in disease suppression at both sites, but was most consistent at WPF, where all soilborne diseases were reduced in both years compared to one of two years at AF. This observation at WPF suggests that the inclusion of the rapeseed crop in the four-year rotation is integral for disease management. In other words, if the rapeseed cover crop is not used, a substantial increase in disease occurs. Research focusing on crop rotation length and sequence have demonstrated disease suppression of black scurf (Larkin and Griffin 2007; Larkin et al. 2010; Larkin and Honeycutt 2006; Peters et al. 2003; Peters et al. 2004), common scab (Larkin and Griffin 2007; Larkin et al. 2010; Wiggins and Kinkel 2005) and silver scurf (Peters et al. 2003), though few, if any, of these studies have observed these effects on an organically-managed site with a history of four-year rotation scheme. Consistent disease suppression with the rapeseed rotation crop and the complementary effects of combined treatments (increased yield from compost and decreased disease from rotation crop) also indicates that the cumulative effects of management practices have not reached a plateau at WPF where further disease suppressive measures are not needed or not effective.

While yield was only increased in a single year by the rapeseed rotation crop, yield increases were observed consistently with the use of the compost. Larkin et al. (2011a) previously reported that a management system including yearly additions of compost had higher tuber yields (increases of 20 % to 60 %) than other systems lacking them, and Larkin and Tavantzis (2013) reported increased total tuber yields utilizing the same compost as this study. Many different factors have been associated with increasing tuber yields, including increasing total soil carbon (Alvarez et al. 2002) and nitrogen (Steinberg 1998) as well as providing organic matter inputs which improve soil structure and water-holding capacity (Johnston 1991). Composts, in general, are capable of impacting one or all of these aforementioned soil properties and causing significant changes in microbial community composition (Bernard et al. 2012; Carrera et al. 2007; Ros et al. 2006), including general increases in overall microbial activity and culturable populations of bacteria and fungi (Bernard et al. 2012), which could all potentially lead to increases in yield.

Despite the beneficial aspects of the compost (increased tuber yield), in multiple years there was an observed increase in tuber disease severity and incidence, as well as in stem and stolon canker, associated with compost amendment. Larkin and Tavantzis (2013) have also reported slight increases in common scab and black scurf severity using the same conifer-based compost on a conventionally-managed agricultural research site. While the variable effects of composts, in general, on plant disease are well documented (Noble and Coventry 2005), management history may also influence whether this particular compost is disease suppressive, since rhizoctonia disease was not reduced in compost amended plots at WPF, even in 2007 despite observed suppression of rhizoctonia disease at AF.

As previously described, the management history at WPF is quite different from that of AF and as such, the overall effects of the compost amendment were greater at AF than WPF, represented a greater relative input of OM and C compared to soil levels, and were associated with corresponding differential effects on soil microbiology and soil microbial characteristics (Bernard et al. 2012). The much higher C and OM background levels at WPF may make the additional inputs in compost amendment less important, since OM is not as much of a limiting factor at WPF as it is at AF. For instance, while compost increased yield in all three years at the conventional site, it only increased yield in two out of three years and to a lesser degree at WPF. This is probably due to the fact that the additional organic matter added in the compost represents a much larger OM input relative to soil levels at AF than at WPF, and consequently had greater overall effects. In fact, given the already high C and organic matter levels in WPF soil, it is somewhat surprising that these compost amendments still provided significant yield increases at WPF, and perhaps indicates that these compost effects may be due to more than just the addition of organic matter, such as changes in soil microbial communities.

Environmental conditions cannot be ignored, as they may have a role in the differing effects of compost amendment on disease between 2007 and the other two years. Overall, 2007 was a relatively dry year, whereas both 2008 and 2009 were much wetter, particularly during the crucial development months of June and July. In dry years, the compost amendment may help retain soil moisture and provide a favorable environment for biological control to work; whereas under wetter conditions, the compost may actually render the soil too wet for effective microbial interactions, reducing or eliminating efficacy in disease reduction, and providing more favorable conditions for the pathogen. For example, *R. solani* prefers cool and wet conditions, as does *H. solani* (Errampalli et al. 2001). Accordingly in the wetter years (2008 and 2009), the compost exacerbated these diseases, but in the driest year of the study, the compost amendment provided control of black scurf and did not exacerbate silver scurf. *S. scabiei*, on the other hand, (causative agent of common scab) prefers warm, dry conditions. Accordingly, in the driest year of the study (2007), common scab severity and incidence were higher than in following years. However, the addition of compost significantly increased the severity of common scab in 2007 and 2008 at AF, and in 2008 and 2009 at WPF (Table 4), despite the fact that control of common scab using vermicompost (Singhai et al. 2011), compost (Al-Mughrabi et al. 2008) and compost teas (Al-Mughrabi et al. 2008; Larkin 2008) has been reported. These observations show that environmental conditions can have a significant impact on the disease suppressive nature of soil amendments, and should always be taken into consideration when devising a disease management strategy.

The impact of rainfall on tuber yields was also very evident in this study. In the wettest year of the study (2008), yield was only increased by 7 % in compost amended plots at AF, and was not significantly higher in compost amended plots at WPF. Whether or not these observations were related to later plant emergence is hard to gauge. In 2007, emergence was much faster than 2008, and emergence was also much faster at WPF than at AF, but emergence rates were not significantly different among treatments. This may indicate that emergence rate is not a good predictor of tuber diseases or yields in response to amendments. As for differences in relative yields between the sites, emergence rate may be a useful indicator, since emergence was faster at WPF than AF and WPF had relatively higher yields in 2007 and 2008 than at AF.

As many biological control organisms are recognized for their disease-suppressive potential (Bénítez et al. 2004; Kloepper et al. 2004), it is not surprising that *B. subtilis* and *T. virens* were able to provide some control of black scurf, common scab and silver scurf in at least one year of the study. *Rhs1A1 also* has been previously shown to provide some control of black scurf (Bandy and Tavantzis 1990; Larkin and Tavantzis 2013). *Rhs1A1* successfully reduced the incidence and severity of black scurf in two years at the conventional site (though only relative to the *B. subtilis* treatment in 2008), and *T. virens* reduced all three tuber diseases in at least one year at the organic site. While reductions in black scurf severity have been reported with the usage of *Rhs1A1* (Bandy and Tavantzis 1990; Larkin and Tavantzis 2013), reduction of common scab severity has only recently been reported (Larkin and Tavantzis 2013), and reduction of silver scurf severity by *Rhs1A1* has not been previously documented. Suppression of common scab and silver scurf by *Rhs1A1* may be related to the potential induction of host defense responses that has been associated with this treatment (Bandy and Tavantzis 1990; Larkin and Tavantzis 2013).

The combination of all of these management practices (rotation crop, compost amendment, biological control amendments) is perhaps the most important aspect of this study, since it provides information on how these treatments function together in an agricultural system, in contrast to most studies which focus on the effects of a single type of treatment on disease suppression. The most important observation from the treatment combinations was that the combined effect of compost amendment and rapeseed rotation crop resulted in lower overall disease severity and incidence in plots following rapeseed, even though compost was responsible for significant overall increases in tuber diseases in some years. In other words, the disease suppressive effect of the rapeseed rotation crop was able to counteract the effect of the compost on soilborne diseases. This is particularly important, since the compost had very positive benefits on tuber yield and thus, the combination of the rapeseed rotation and the compost amendment was complementary, illustrating both positive disease suppression and yield benefits.

Other combinations of treatments generally resulted in smaller and statistically insignificant additive effects. Although the combination of compost and *Rhs1A1* was marginally more effective at controlling black scurf in 2007 at AF, in most cases the addition of biocontrol organisms to either the compost or rotation treatments did not significantly enhance disease control. Overall, combined effects of biocontrol organisms with the other treatments were minimal, as biocontrol effects were overshadowed by the stronger effects of the rotation crop and/or compost amendment. Compost amendments and rapeseed rotation crops would be expected to have a much larger effect on the soil microbial community than individual biological control organisms, as has been demonstrated previously (Larkin 2008). The addition of substrate carbon with compost amendment and rapeseed green manures affects many different edaphic factors, including soil microbial communities, whereas biological control organisms have very specific effects on an individual microorganism or subset of the soil microbial population, and also may or may not be able to survive and persist for appreciable periods after they are incorporated into the soil.

The combined beneficial effects of certain treatment combinations demonstrates a compatibility between these practices that can be utilized to design effective management programs for disease suppression and yield optimization to achieve beneficial effects on tuber quality and yield (less yield loss). While individual treatments by themselves may be effective to some extent, in combination with other treatments they can have much more beneficial results. The rapeseed rotation was successful at controlling all diseases in at least one year at each site, though it was not particularly effective at increasing tuber yields. On the other hand, although compost amendment had variable effects on disease (reducing some disease parameters in one year and increasing disease in other years), it consistently increased total and marketable tuber yield. Thus, the combined effects of the rapeseed rotation and the compost amendment resulted in disease suppression and increased yields. The biocontrol amendments were also marginally successful at controlling tuber diseases, in particular *Rhs1A1* significantly reduced incidence and severity of black scurf and *T. virens* reduced multiple diseases in at least one year at AF and WPF, respectively. Thus, the addition of biocontrol organisms, although not as consistently effective, provides increased potential for disease reduction when conditions are favorable, and add another beneficial aspect to the total package. Perhaps most importantly, this research demonstrated that these treatments and their combinations can be effective approaches for reducing disease and increasing yield under both conventional and organic production practices, and under a variety of cropping backgrounds and management histories.

This study has revealed that none of the individual treatments utilized here can function as a “silver bullet” in terms of reducing disease and increasing yield. Rather, each treatment has specific benefits that can address particular problems in an overall management strategy. For example, for sites with substantial disease problems, a rapeseed rotation crop may provide enhanced suppression. On the other hand, those sites with an effective disease management program may consider the usage of a compost amendment to increase yields (as the increase in disease may be only marginal). Additional consideration should be given to the usage of the compost amendment and compost amendments in general, as it is possible that this compost may be effective at suppressing disease in different environmental conditions (drier) or that a more suitable compost could be found that achieves both yield increases and effective disease suppression. Finally, both organic and conventionally-managed sites could benefit from the use of biological control organisms to help in the management of black scurf and other soilborne diseases. As this study has demonstrated, the implementation of management strategies designed to control disease and increase yields must focus not only on individual treatments, but their combinations and how they interact with one another, as well as how they function at sites with different backgrounds. Future research must further address the differential effects of treatments on different sites, and their abilities to reduce disease and increase yield alone and in combination. Furthermore, it should be recognized that results may vary based on the particular site where the practices are implemented, and this taken into consideration when designing and implementing an effective management strategy.

Acknowledgements We would like to thank Leanne Matthiesen, Gary Sewell, Roger Jardine, Jim Gerritsen, Randy Smith, Ethel Champaco, Megan Patterson, Renee Rioux, Kristopher Cooper, Jen Brown, Sara Caldwell, Stephanie Cash, Caleb Gerritsen, Peter Gerritsen, Ryan Guillemette, Katie Moulton, Kylie Palmer, Katie Priest, Benjamin Richard, and Valerie Shaffer for technical assistance. This research was supported in part by the USDA Organic Transition Grant 2007-51106-03791, the Northeast IPM Grant 2007-34103-17076 and Hatch Grant. This is Maine Agricultural and Forest Experiment Station Publication No. 3344.

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