Am. J. Potato Res. (2014) 91:429–439
DOI 10.1007/s12230-014-9366-z

Management Effects of Disease-Suppressive Rotation Crops on Potato Yield and Soilborne Disease and Their Economic Implications in Potato Production

Robert P. Larkin · John M. Halloran

Published online: 24 January 2014

Abstract Soilborne potato diseases are persistent problems in potato production. Use of disease-suppressive rotation crops, such as *Brassica* spp. (mustards, rapeseed) and sudangrass, has shown potential for management of soilborne diseases and enhanced yield in various crop production systems. However, how to best implement these crops into productive potato cropping systems has not yet been determined. In this research, potential disease-suppressive crops were evaluated under four different types of production management (as a cover crop, green manure, harvested crop-residue incorporated, and harvested crop-residue not incorporated) in potato rotation field trials, and their effects on disease, yield, and economic viability determined. Mustard blend, sudangrass, and rapeseed rotations reduced the tuber disease black scurf (by 16–27 %) and increased yield (by 6–11 %) relative to a barley rotation control, but only mustard blend consistently reduced common scab (by 11 %). All rotation crops managed as green manures produced lower disease (by 15–26 %) and higher yields (by 6–13 %) than other management practices. Overall, the combination of mustard blend managed as a green manure was most effective, reducing scurf by 54 % and increasing yield by 25 % relative to a soybean cover crop. The use of mustard or rapeseed as a harvested crop with incorporation provided the best economic return, increasing net income by more than $860/ha relative to the standard barley rotation, but mustard blend grown as a green manure or non-incorporated harvest crop also substantially increased net income ($600 to $780/ha).

Resumen Las enfermedades de la papa en el suelo son problemas persistentes en su producción. El uso de rotación de cultivos para suprimir las enfermedades, tales como *Brassica* spp. (mostaza, colza) y pasto sudán, ha mostrado potencial para el manejo de las enfermedades del suelo y ha aumentado el rendimiento en varios sistemas de producción del cultivo. No obstante, aún no está determinado cómo implementar de la mejor manera estos cultivos en los sistemas productivos en el cultivo de papa. En esta investigación, se evaluaron cultivos con potencial supresivo de enfermedades bajo cuatro diferentes tipos de manejo de la producción (como cultivo de cobertura, abono verde, incorporación de residuos del cultivo después de cosecha, y residuos del cultivo no incorporados) en ensayos de campo de rotación en papa, y sus efectos en enfermedad, rendimiento, y en determinada viabilidad económica. Las rotaciones con la mezcla de mostaza, pasto sudán y colza redujeron la enfermedad de la costra negra del tubérculo (de 16–27 %) y aumentó el rendimiento (de 6–11 %) en relación a una rotación con cebada como testigo, pero la mezcla de mostaza sola redujo consistentemente la roña común (en un 11 %). Todas las rotaciones de cultivo manejadas como abonos verdes produjeron más baja enfermedad (en 15–26 %) y más altos rendimientos (de 6–13 %) que otras prácticas de manejo. En general, la combinación de la mezcla de mostaza manejada como abono verde fue la más efectiva, reduciendo la costra negra en un 54 % y aumentando el rendimiento en un 25 % en relación a un cultivo de cobertura de soya. El uso de mostaza o colza como cultivo cosechado con incorporación suministró la mejor ganancia económica, incrementando los ingresos netos por más de $ 860/ha en relación con la rotación convencional con cebada, pero la mezcla de mostaza cultivada como abono verde o como cultivo cosechado no incorporado también aumentó substancialmente el ingreso neto (de $ 600 a $ 780/ha).

Keywords Biofumigation · Brassica · Cropping systems · Economic potential · Green manure · Rhizoctonia solani · Streptomyces scabies

Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

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

Introduction

Soilborne diseases are persistent, recurrent problems in potato (*Solanum tuberosum* L.) production, resulting in reduced plant growth and vigor, lower tuber quality, and reduced yield. Of particular concern throughout the Northeast due to their constant presence, are the tuber diseases black scurf, caused by *Rhizoctonia solani* Kühn, and common scab, caused by *Streptomyces scabies* (Thaxter) Lambert & Loria. These and other soilborne diseases can be difficult to control, and current control measures, such as regular crop rotation, chemical seed treatments, promoting rapid emergence of sprouts and early harvest of tubers, (Powelson et al. 1993; Secor and Gudmestad 1999; Stevenson et al. 2001) are not always practical or effective. Alternative or supplemental management practices are needed.

Crop rotation, in general, is known to be important to maintain crop productivity and reduce build-up of soilborne pathogens and diseases (Cook 1986, 2000; Krupinsky et al. 2002). In potato, 2-year rotations have been shown to reduce soilborne disease levels compared to continuous potato (Honeycutt et al. 1996; Specht and Leach 1987), but longer rotation lengths of 3 or 4 years between potato crops are known to be more effective in controlling soilborne diseases (Carter and Sanderson 2001; Hide and Read 1991; Hoekstra 1989; Peters et al. 2003, 2004; Scholte 1987). However, another important function of crop rotations is that they also need to increase profitability, either in the addition of profitable rotation crops themselves or in increased production or reduced losses of the potato crop (Halloran et al. 2005).

Most crops that are not hosts to the same pathogens as the primary crop are considered suitable rotation crops, which for potato have traditionally been primarily small grain crops, such as barley (*Hordeum vulgare* L.) and oats (*Avena sativa* L.). Such rotation crops result in disease reduction primarily by serving as a break in the host-pathogen cycle. However, there may be substantial differences among different crop types, species, and cultivars in their effects on soilborne diseases and productivity. Rotation crops that have specific and active mechanisms for reducing soilborne diseases are considered disease-suppressive crops, and can result in substantially greater reductions in disease than standard or non-suppressive crops. For example, crops in the *Brassicaceae* family (which include broccoli, cabbage, cauliflower, turnip, radish, canola, rapeseed, and various mustards) used in rotations or as green manures have been observed to reduce soilborne diseases or populations of fungal pathogens and nematodes (Brown and Morra 1997; Larkin and Griffin 2007; Matthiessen and Kirkegaard 2006; Smolinska and Horbowicz 1999), and to improve soil characteristics and crop yield (McGuire 2003). Sudangrass and sorghum-sudangrass hybrids have also been shown to reduce soilborne diseases in previous studies (Davis et al. 1996, 2004, 2010). Both of these groups employ biofumigation as a mechanism of action, which refers to the breakdown of plant metabolites in soil to produce volatile compounds that are toxic to many soil microorganisms, as well as nematodes and weed seed (Sarwar et al. 1998). Further studies have indicated that additional mechanisms, including specific changes in soil microbial communities unrelated to levels of toxic metabolites, are also important in the reduction of soilborne diseases by these crops (Cohen et al. 2005; Larkin and Griffin 2007; Mazzola et al. 2001).

Of course, how a particular rotation crop is managed may also greatly influence the resulting effects on the subsequent crop, including disease levels and crop production, as well as economic factors. Rotation crops can be managed as full season harvested crops, thus providing an economic return; as full season or partial season cover crops, where there is no harvest and plant residues are left in place; or grown as a green manure, where all plant biomass is incorporated into the soil while still fresh and green. Each approach has advantages and disadvantages, which have been described in reviews dealing with crop rotations, cover crops, and green manures (Cherr et al. 2006; Fageria 2007; Fageria et al. 2005; Magdoff 2000; Magdoff and van Es 2009; Sarrantonio and Gallandt 2003). Biofumigation crops have generally primarily been used as green manures, in order to get the most out of their biofumigation potential, but there may also be benefits derived from other uses.

In our own research, we previously evaluated some of these crop rotations and cropping systems for improved management of soilborne potato diseases, observing that Brassica rotations, such as canola or rapeseed, or mustard green manures, significantly reduced soilborne diseases (Larkin and Griffin 2007; Larkin et al. 2010, 2011a, b). Most of these previous trials used the disease-suppressive crops as full-season green manure crops, but in some cases, reductions in soilborne diseases were also observed without incorporation of fresh biomass (Larkin et al. 2010). In warmer climates, such as the western US, these disease-suppressive crops can be grown as a fall-planted green manure crop following another spring-summer season crop. However, the short growing season in cooler climates, such as in the northeastern US and Atlantic Canada, makes this approach less practical.

Although previous research has indicated the potential of *Brassicas* to reduce multiple diseases, it has not yet been established just which crops are best for controlling specific diseases, how to manage these crops for the most effective and economical results, and how to best implement these crops into a potato production system. That is, the best ways to utilize these practices and incorporate them into productive cropping systems, particularly in the northeastern US and Canada, have not been established. 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 oilseed Brassica (canola, rapeseed, or radish), can be effective in reducing disease, or if the *Brassica* crop can be effective as a fall-planted green manure 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. The objectives of this research were to evaluate several types of potential disease-suppressive rotation crops managed in different ways (as green manures, harvested crops, cover crops) for their effects on soilborne potato diseases and tuber yield in field trials in Maine, and to determine the economic practicality of the different approaches by conducting an economic analysis comparing the costs and returns for each system.

Materials and Methods

Treatments

There were two treatment factors, rotation crop (ROT), consisting of 5 different rotation crops, and management practice (MAN), which consisted of 4 different management practices for each crop. Rotation crops used were: 1) Mustard blend—'Caliente 119' (blend of oriental and white mustard seeds, *Brassica juncea* L. and *Sinapis alba* L.); 2) Sorghum-Sudangrass hybrid (*Sorghum bicolor* × *S. bicolor* var. *sudanense* L.); 3) Rapeseed—'Dwarf Essex' (*Brassica napus* L.); 4) Soybean (*Glycine max* L.), used to represent a non-disease-suppressive rotation crop; and 5) barley (*Hordeum vulgare* L.) underseeded with red clover (*Trifolium pretense* L.), used to represent a typical or standard rotation crop commonly used. Each rotation crop was then managed in four different ways: 1) as a green manure, in which all biomass produced would be incorporated into the soil while plants were fresh and green; 2) as a cover crop, in which all biomass produced would remain in place (no action taken) and allowed to overwinter (no incorporation); 3) as a harvested crop (such as for seed, grain, etc.), then remaining crop residue incorporated into soil after harvest; and 4) as a harvested crop (seed, grain, etc.), but residue not incorporated after harvest. Note that incorporation here refers specifically to the incorporation of plant residues at the end of the summer, immediately after harvest (for harvested crops), and not any subsequent activities (all treatments would receive regular tillage and field preparation for planting the following spring).

Field Design and Management

Experimental plots were established at the USDA-ARS New England Plant, Soil and Water Laboratory Field Experimental Site in Presque Isle, ME utilizing a split-plot design with 4 replicate blocks, with rotation crop and management practice as the main and split factors, respectively. Soil type was a Caribou sandy loam (Fine-loamy, isotic, frigid Typic Haplorthods). Two adjacent fields with identical experimental design and set-up were established in 2008 and 2009, respectively, to establish the rotation crops and subsequent potato crops (in 2009 and 2010, respectively) in each field. Thus, 2 years of potato data could be obtained from independent fields over a 3-year period (2008–2010). Each main plot was 7.6 m long by 14.6 m wide, and each split-plot was 7.6 m× 3.6 m, and consisted of 4 potato rows. Main plots were separated by uncultivated buffer strips of 6.1 m on all sides.

All rotation crops were planted in early June using standard practices, and were managed using recommended production practices, including fertilizer rates, pesticide applications, and weed control measures for that particular crop. For the green manure management treatment, rotation crops were flail mowed in mid-August, and then immediately incorporated into the soil using a roto-tiller. For the harvested treatments, above-ground plant portions were removed using a seed or grain combine or mower, and then remaining stubble and residue was incorporated using a roto-tiller for the harvest-incorporated treatment only. For the harvest-not incorporated treatment, stubble remained and was left intact. For the cover crop treatment, all biomass and residues were left untouched throughout the cropping season and allowed to overwinter (as dead plants) until the following spring.

For the potato crop, in the following spring after the rotation crop treatments, all plots received primary tillage with a chisel plow and then secondary tillage of one to two diskings prior to planting. Cut seed pieces of potato variety 'Russet Burbank' were planted by hand in each plot (four rows, 0.9 m centers, with a 35 cm spacing between plants). Potato plots were fertilized with the equivalent of 224 kg ha^{-1} N and 249 kg ha^{-1} P_2O_5 and K_2O. In-season cultivation included one or two shallow passes with a cultivator, and one pass with a hiller. Potato plots were also sprayed regularly throughout the growing season with alternating applications of mancozeb and chlorothalonil at recommended rates for the control of late blight.

In an additional side experiment to assess the feasibility of fall-grown Brassica for use as a fall green manure crop following some other summer crop, individual field tracts (7.6 m by 7.3 m) were planted with rapeseed (cv. 'Dwarf Essex') on four sequential planting dates (August 1, 15, September 1, 15). Plant growth and biomass were monitored throughout fall, for potential incorporation by late October. Above-ground biomass samples were collected from randomly placed 1 m^2 sampling grids in each plot, and average biomass expressed as kg/ha.

Disease and Yield Evaluations

Potato plants were monitored in the field for signs and symptoms of soilborne diseases. All potatoes were harvested from the middle two rows of each plot, and subsequently washed, graded, and rated for incidence (% of tubers showing symptoms) and severity (% of tuber surface covered) of black scurf and common scab, as well as for the occurrence of any other tuber diseases or anomalies. For more meaningful presentation, incidence data was expressed as the incidence of substantial disease, calculated as the percentage of tubers above a threshold disease rating of 2 % severity, which indicates disease levels that may affect tuber quality and raise marketability issues. This index was used to represent incidence for all data presented, and provides a useful indicator for assessing disease problems. Yield was evaluated as the total and marketable (>4.8-cm diam) weight of potatoes per 7.6-m harvest row and converted to the equivalent value expressed as Mg/ha.

Economic Analyses

A partial budgeting approach was employed to determine cost differences and their impact on net revenue (Olsen 2003). Partial budgeting includes only those costs that vary from one enterprise (system) to another. For example, since all systems used the same potato planting and maintenance operations, those costs were the same for all systems, and are not included. Costs that varied for the different rotation crops were primarily seed, fertilizer, pesticide, and maintenance and application costs. Costs that varied for the different management practices were associated with different harvest and post-harvest operations. For example, green manure crops required additional mowing and incorporation operations, and harvested rotation crops included harvesting costs that were not a part of cover crops operations. Production costs were adapted and updated from enterprise budgets established for previous similar studies (Halloran et al. 2008, 2013; Larkin et al. 2010, 2011b), as well as other published sources (Amosson et al. 2011; Ontario Ministry of Agriculture 2013). To evaluate the differences in costs related to the treatment factors, associated costs were determined on an annual basis as well as for the full 2-year rotation period. Costs for the 2-year rotation includes all costs for each rotation crop (costs of seed, planting, tillage, crop maintenance), including crops that derive no revenues (green manure, cover crop).

Additional economic data included total and marketable yields for potato, average potential yields for the rotation crops, and the revenue that would be generated for each system. Revenue was determined for the potato crop from observed tuber yield values based on average market prices for Maine for each harvest year (USDA, NASS 2010). Potential revenue from harvested rotation crops was estimated from average crop yield and market prices for Maine (where available) or national averages and prices for each year (USDA, NASS 2010, 2013). Costs and revenues were used to calculate gross and net revenue for each system over the course of the study.

Statistical Analyses

Soilborne disease and yield estimate data were analyzed using standard analysis of variance (ANOVA) with factorial treatment structure and interactions based on the split-plot experimental design. Data from each crop year were analyzed separately, and then data from the 2 years (2009–2010) were also combined and analyzed together (with year as an additional factor) to evaluate average and multi-year effects of the treatments. Significance was evaluated at $P<0.05$ for all tests. Mean separation was accomplished with Fisher's protected LSD test. All analyses were conducted using the Statistical Analysis Systems ver. 9.1 (SAS Institute, Cary, NC).

Results

Growing Conditions, Disease, and Crop Development

Environmental conditions over the course of the study were within normal ranges for the area, but there were some differences among years. Summer rainfall in 2008 and 2009 were close to average values, providing adequate moisture for normal crop growth, whereas rainfall was lower in 2010, particularly from mid-July through August (Table 1), creating some stresses on tuber production. Average daily temperatures tended to be somewhat lower than normal in 2009 and higher than normal in 2010. Thus, 2010 tended to be hotter and drier than the average, and 2009 cooler, but overall, conditions were favorable for potato production and disease development. The primary potato diseases observed in each of the potato seasons assessed were black scurf and common scab on the tubers. Overall, black scurf levels were low (covering 0.5 to 1.0 % of tuber surface area) in both years. For common scab, however, somewhat high levels (8 to 14 % surface coverage) of mild tuber surface lesions were observed throughout the study. Other potential soilborne diseases, such as silver scurf, black dot, and powdery scab, were not observed at any time during the study. Tuber yields were typical for this area and variety at both sites, with total overall yield ranging from 24 to 40 Mg/ha, and overall yield averaging higher in 2009 than 2010. Despite the differences in environmental conditions and some significant year effects, overall results for disease and yield were similar each year, and combined results for both years are most representative of the data. Rotation crop and management practice both significantly affected disease development and tuber yield. However, there were no significant rotation crop by management practice interactions for any parameter. Thus all data are presented as main effects for the two factors.

Table 1 Total rainfall and average daily temperature for the months May to September for 2008 to 2010 at the field research site in Presque Isle, ME compared with long-term (30-year) average conditions

Location month	Rainfall (cm)[a]				Average daily air temperature (°C)[a]			
	2008	2009	2010	Long-term avg	2008	2009	2010	Long-term avg
Presque Isle								
May	5.3	12.5	6.5	8.7	10.3	11.3	13.1	11.4
June	11.6	8.6	13.0	8.6	15.9	14.7	16.2	16.4
July	8.2	12.2	7.2	9.4	20.4	13.4	20.8	19.0
August	11.2	5.9	3.3	10.0	17.7	15.9	18.8	18.2
September	7.9	3.8	7.2	8.7	13.6	11.7	14.6	13.2
Total	44.2	43.0	37.2	45.4	77.9	67.0	83.5	78.2

[a] Rainfall and temperature data were compiled from an on-site weather data logger. Long-term average data was compiled from the NOAA National Climatic Data Center local monitoring information for Presque Isle, ME

Treatment Effects on Disease Development

All three potential disease-suppressive rotations (mustard blend, sudangrass, and rapeseed), significantly reduced the incidence of black scurf tuber disease (by 28 to 35 %) relative to the standard barley rotation treatment, and reduced the severity of black scurf (by 15 to 27 %) relative to both the soybean and barley rotation treatments over both years of the study (Table 2). Mustard blend also significantly reduced incidence relative to soybean rotation. For common scab, only mustard blend and soybean rotations reduced the severity of scab (by 11 to 13 %) relative to the barley rotation.

Management practice also significantly affected disease development, with management as a green manure for all rotation crops providing significant reductions in both black scurf (26 to 41 %) and common scab (11 %) relative to management as a cover crop (Table 2). In addition, rotations managed as a harvested crop, then incorporated, also significantly reduced black scurf (by 12 to 29 %) and common scab (10 %) relative to a cover crop. Whereas crops harvested but not incorporated resulted in disease levels comparable to a cover crop for black scurf, but did reduce common scab severity (by 10 %) (Table 2).

Treatment Effects on Tuber Yield and Development

Mustard blend rotations significantly increased total and marketable tuber yield in a subsequent potato crop (by 8 to 12 %) relative to both soybean and barley rotations, regardless of management practice (Table 3). Sudangrass and rapeseed rotations also increased marketable yield relative to soybean and barley rotations (9 to 13 %), and sudangrass rotation increased total yield relative to a barley rotation (by 6 %) (Table 3). Mustard blend also reduced the percentage of grossly misshapen tubers, a measure of tuber quality, by 36 to 43 % relative to all other rotation treatments (Table 3).

Management of rotations as a green manure resulted in significantly greater total tuber yield than all other management practices for all rotation crops combined, with a 12 % increase relative to cover crop management (Table 3). Green manure management also increased marketable tuber yield by 13 % relative to cover crop management for all rotation crops. Rotations that were harvested-then incorporated also increased yield relative to cover crop management for both total and marketable tuber yield, but with somewhat smaller increases (6 to 8 %) than observed with green manure management.

Combined Effects

The effect of management as a green manure was consistent across all rotation crops, resulting in a 10 to 16 % increase in total yield (average increase 12.5 %) with each rotation crop relative to cover crop management (Fig. 1). The harvest w/incorporation management also increased yield across all rotations, but to a lesser degree (2 to 12 % increase, average of 7 %). And because mustard produced relatively higher potato yields overall, the combination of mustard blend rotation and green manure management produced the overall highest yield. Likewise for soilborne diseases, green manure management reduced black scurf severity by 10 to 33 % relative to cover crop management across all rotation crops, and mustard blend resulted in the lowest disease among the rotation crops (Fig. 2). Thus, when both the rotation crop and management practice are considered together, the mustard blend rotation managed as a green manure provided the best overall results, increasing yield and decreasing soilborne disease relative to other treatment combinations. Overall, the combination of Mustard blend rotation crop and green manure management practice resulted in total tuber yield that was 25 % greater, as well as a reduction in black scurf severity of 54 %, compared to a soybean cover crop system. However, the management

Table 2 Effect of different crop rotations and crop management practices on tuber diseases (severity and incidence of black scurf and severity of common scab) over two field seasons (2009–2010)

Treatment factors	Disease parameters		
	Black scurf		Common scab
	Severity (% of surface)	Incidence (% of tubers)	Severity (% of surface)
Rotation crop			
Mustard blend	0.66 b[y]	9.2 c	6.89 b
Sudangrass	0.74 b	9.8 bc	7.30 ab
Rapeseed	0.76 b	10.1 bc	7.30 ab
Soybean	0.90 a	13.6 ab	6.73 b
Barley/clover	0.89 a	14.1 a	7.70 a
LSD (P=0.05)	0.12	3.7	0.67
Management practice			
Green manure	0.65 c	8.2 b	6.93 b
Harvested-incorporated	0.77 b	9.9 b	6.98 b
Harvested-not incorporated	0.85 ab	13.4 a	6.99 b
Cover crop	0.88 a	13.9 a	7.81 a
LSD (P=0.05)	0.11	3.3	0.60
ANOVA		P values	
Rotation (ROT)	0.0003	0.0212	0.0446
Management (MAN)	0.0002	0.0015	0.0099
ROT × MAN	0.7161	0.7833	0.0703

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

practice of harvesting the rotation crop, then incorporating the residue, particularly in combination with mustard blend, sudangrass, and rapeseed, also increased tuber yield (by 10 to 20 %) (Fig. 1) and reduced black scurf severity (by 26 to 41 %) relative to cover crops of soybean and barley (Fig. 2).

Economics of the Rotation Crop and Management Practices

Variable pre-harvest production costs, determined primarily by the costs of seed, fertilizer, and pesticide requirements for each of the rotation crops, showed similar overall costs,

Table 3 Effect of different crop rotations and crop management practices on tuber yield (total and marketable yield) over two field seasons (2009–2010)

Treatment factors	Tuber yield (Mg/ha)		
	Total yield	Marketable yield	Percent misshapen
Rotation crop			
Mustard blend	36.6 a[y]	28.7 a	5.6 b
Sudangrass	35.2 ab	29.1 a	9.2 a
Rapeseed	34.9 abc	28.4 a	9.3 a
Soybean	34.0 bc	25.7 b	9.9 a
Barley/clover	33.1 c	26.0 b	8.8 ab
LSD (P=0.05)	2.0	2.2	3.3
Management practice			
Green manure	37.0 a	29.2 a	6.6 a
Harvested-incorporated	34.9 b	28.0 a	8.9 a
Harvested-not incorporated	33.5 bc	27.3 ab	9.5 a
Cover crop	32.9 c	25.9 b	9.2 a
LSD (P=0.05)	1.8	2.0	2.9
ANOVA		P values	
Rotation (ROT)	0.0283	0.0014	0.0849
Management (MAN)	0.0002	0.0259	0.2190
ROT × MAN	0.9005	0.1428	0.9908

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

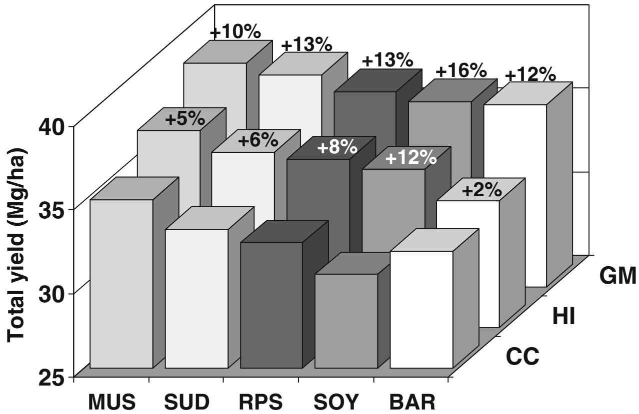

Fig. 1 Effect of management of rotation crops as a green manure (GM), cover crop (CC), or a harvested crop-w/residue incorporated (HI), for each rotation crop on subsequent potato tuber yield. Data averaged over 2 years (2009–2010) of field trials. Rotation crops: *MUS* Mustard Blend, *SUD* Sudangrass hybrid, *RPS* Rapeseed (disease-suppressive crops), *SOY* soybean (nonsuppressive control), *BAR* barley/clover (standard rotation). Values over bars indicate percent increase in yield relative to CC for each rotation

ranging from \$323 to \$398/ha among the rotation crops (Table 4). The total variable costs included harvest and post-harvest operations, and thus varied among the management practices for each rotation crop (\$358 to \$508/ha), with lowest cost being observed for the cover crop management practice, because no harvest and post-harvest operations were involved. Highest cost was associated with the Harvest-then incorporate practice, since this involved the additional incorporation operation after harvest.

Potential gross rotation incomes, determined from average Maine and national yields and prices for each year, ranged from \$519 to \$1,037/ha, with sudangrass on the low end to soybean on the high end (Table 4). Substantially higher revenue provided by rapeseed relative to mustard was a result of consistently higher yields for rapeseed (1.9 vs. 1.0 Mg/ha). Low returns for sudangrass were due primarily to lower crop values. Since only the HI and HN management practices result in an economic return for the rotation crop, net rotation returns for the CC and GM practices were negative and equal to the total production costs for those systems. For the HI and HN practices, potential positive net returns of \$21 to \$604/ha were observed, with the lowest returns for sudangrass and highest returns for rapeseed and soybean rotations (Table 4).

Both rotation crop and management practice had dramatic effects on the economic return of the subsequent potato crop, as was previously reflected by the changes in tuber yield (Fig. 1). The mustard blend rotation and green manure management practice resulted in the highest returns from the potato crop, but the sudangrass and rapeseed rotation and HI management also resulted in substantial increases in income return relative to a barley rotation managed in the usual way

Table 4 Effects of different crop rotations and crop management practices on variable production costs and rotation crop returns (\$/ha) over a 2-year trial period (2009–2010)

Rotation crop	Crop management practice[a]				
		GM	HI	HN	CC
Costs	Pre-harvest		(\$/ha)		
	Variable costs		Total variable costs		
Mustard blend	358	403	468	438	358
Sudangrass	388	433	498	468	388
Rapeseed	323	368	433	403	323
Soybean	364	409	501	471	364
Barley/clover	398	443	508	478	398
Returns	Gross rotation				
	Income[b]		Net rotation return[b]		
Mustard blend	642	−403	174	204	−358
Sudangrass	519	−433	21	51	−388
Rapeseed	1,005	−368	572	602	−323
Soybean	1,037	−409	536	566	−364
Barley/clover	655	−443	147	177	−398

[a] Management practices: *GM* Green manure, where all plant biomass is incorporated into soil while fresh; *HI* Harvested-then incorporated, where the rotation crop is first harvested for seed, grain, or forage, then residues incorporated; *HN* Harvested-not incorporated, where rotation crop is harvested, then residues remain in place; and *CC* Cover crop, where all plant biomass is left in place, undisturbed to overwinter

[b] Gross rotation income is based on average annual yield data and average crop price data for Maine (where available) or the US (USDA, NASS 2010) for each crop averaged over the two production years. Only the management practices that involve harvesting the rotation crop (HI, HN) receive income from the rotation crop, thus for GM and CC the net rotation return is the same as the total variable production costs

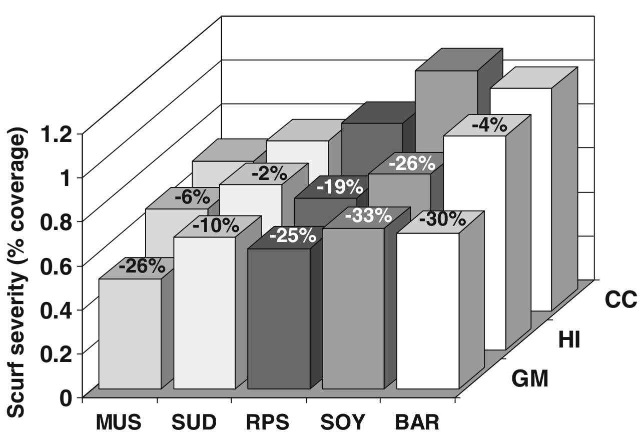

Fig. 2 Effect of management of rotation crops as a green manure (GM), cover crop (CC), or a harvested crop-w/residue incorporated (HI) for each rotation crop on disease severity of black scurf on the subsequent potato tuber crop. Data averaged over 2 years (2009–2010) of field trials. Rotation crops: *MUS* Mustard Blend, *SUD* Sudangrass hybrid, *RPS* Rapeseed, *SOY* soybean (nonsuppressive control), *BAR* barley/clover (standard rotation). Values over bars indicate percent decrease in scurf severity relative to CC for each rotation

(HN type), with gains in potato income from $488 to $1,219/ha (Table 5). Crops managed strictly as a cover crop resulted in the lowest yield returns, which were less than those from the standard barley rotation for most crops. However, mustard blend, even when grown strictly as a cover crop, provided a substantial increase in yield return over the barley control.

Taking all costs and revenues into consideration for both the rotation and potato phase of the production operation, the net change in income for the different crops and management systems ranged from substantial decreases to substantial increases depending on the specific combinations. Lowest income totals, representing decreases relative to a standard barley rotation, were observed with the CC management option for all rotations, with the exception of mustard blend, which managed to produce comparable income to the standard barley rotation, even when grown solely as a cover crop (Table 5). Highest overall net income increases were observed for the mustard blend and rapeseed rotations that were managed as a harvested crop, then incorporated (HI), with increases of $861 to $883/ha. Also resulting in substantial overall increases in net income was the mustard blend rotation managed as GM or HN, soybean managed as HI or HN, and rapeseed managed as HN ($580 to $780/ha). To a lesser degree, but still providing positive returns was sudangrass managed as GM or HI ($420 to $454/ha) (Table 5).

Table 5 Effect of different crop rotations and crop management practices on economic return from subsequent potato crop and net income change over 2-year rotation relative to a standard barley (harvested-not incorporated) rotation

Rotation crop	Crop management practice[a]			
	GM ($/ha)	HI	HN	CC
Change in yield return from subsequent potato crop				
Mustard blend	1,219	864	753	488
Sudangrass	1,064	576	377	89
Rapeseed	842	488	155	−89
Soybean	709	355	288	−510
Barley/clover	665	−66	0	−199
Net income change (including rotation and potato years)				
Mustard blend	639	861	781	19
Sudangrass	454	420	250	−476
Rapeseed	297	883	580	−589
Soybean	123	714	677	−1,051
Barley/clover	45	−96	0	−774

[a] Management practices: *GM* Green manure, where all plant biomass is incorporated into soil while fresh; *HI* Harvested-then incorporated, where the rotation crop is first harvested for seed, grain, or forage, then residues incorporated; *HN* Harvested-not incorporated, where rotation crop is harvested, then residues remain in place; and *CC* Cover crop, where all plant biomass is left in place, undisturbed to overwinter

Fall Planting Results

Attempts to use the Brassica rapeseed rotation as a fall-only green manure crop were not encouraging. Only the August 1 planting date produced substantial plant biomass (~2,000 kg/ha) and would be appropriate for use as a green manure crop. Plantings from Aug 15 and later resulted in sparse germination and emergence, and plants grew little after initial emergence due to onset of cold weather in September. Plant biomass (dry weight) from the later planting dates ranged from <800 kg/ha (Aug. 15) to <100 kg/ha (Sep. 15). Although most plants survived until the planned mid-October incorporation date, there was relatively little plant growth or biomass produced, and not enough to be useful as a green manure.

Discussion

In this research, different types of disease-suppressive crops, representing a Brassica with high biofumigation potential (mustard), a Brassica with lower biofumigation potential (rapeseed), and a non-Brassica biofumigation crop (sorghum-sudangrass hybrid), were compared with a standard rotation crop (barley) and a non-suppressive rotation crop (soybean) for their effects on yield and soilborne diseases of a subsequent potato crop. In addition, different management approaches, including use as a cover crop, harvested crop, harvested crop w/residue incorporated, and as a green manure, were evaluated for each crop and their relative economic implications determined.

Overall, the mustard blend was most effective of the rotation crops, reducing black scurf and common scab and increasing yield to a greater extent than most other rotations, although sudangrass and rapeseed also were effective to some extent. In previous studies, mustard, rapeseed, and sudangrass have also been shown to reduce these and other soilborne potato diseases, including stem canker, verticillium wilt, silver scurf, and powdery scab, as well as increase tuber yield (Bernard et al. 2014; Davis et al. 1996; Larkin and Griffin 2007; Larkin et al. 2010, 2011a, b, 2012).

In general, all rotation crops were more effective when used as a green manure rather than as a cover crop, regarding the reduction of black scurf and increased potato tuber yield. Since there were no significant crop by management interactions, and all rotations provided a similar response, it suggests that Brassicas may not necessarily be 'better' as green manures than other crops. Although the Brassica and disease-suppressive crops performed better than the other crops overall, they were not necessarily better as green manures than other rotations (similar relative improvement vs. other practices). This indicates that the incorporation of fresh organic matter and the organic C inputs in the plant biomass green manures may be the most important component for providing beneficial effects on disease and yield, rather than the specific biofumigation effects. Green manures have been shown to result in larger organic matter inputs than traditional crop rotations or cover crops, producing improvements in soil fertility and structure (McGuire 2003, 2012), increased microbial biomass and activity (Abdallahi and N'Dayegamiye 2000; Cherr et al. 2006; Fageria 2007; Grandy et al. 2002; Little et al. 2004; MacRae and Mehuys 1985; Thorup-Kristensen et al. 2003) as well as significant changes in soil microbial community characteristics (Chander et al. 1997; Goyal et al. 1992, 1999; Liu et al. 2010), and they also change microbial communities in ways that are distinctly different from other types of organic matter amendments, such as manure or sawdust (Collins et al. 2006; Larkin et al. 2010, 2011b; Stark et al. 2007) Thus, green manures can provide benefits to a subsequent potato crop, regardless of the specific crop type used.

However, growing the biofumigation crops with any management practice provided disease and yield benefits relative to the control crops, and these benefits were apparently a direct result of their disease-suppressive capabilities. Although most effective as green manures, the biofumigation crops still resulted in significant reductions in disease and increased yield when used as harvested crops and even when used as cover crops, indicating that these crops still provide positive benefits even when not incorporated fresh into the soil (HN, CC). Previously, most studies using biofumigation disease-suppressive crops have focused on the need to utilize these crops as green manures for sufficient efficacy (Kirkegaard et al. 1993; Matthiessen and Kirkegaard 2006; Sarwar et al. 1998). However, some studies have shown that canola and rapeseed crops could reduce disease and increase yield when grown as standard rotation crops and not incorporated (Larkin et al. 2010). Although biofumigation is the presumed mechanism of action for these crops, additional studies have indicated that additional mechanisms, including specific changes in soil microbial communities not related to levels of glucosinolate or other toxic metabolites, may be just as important in the reduction of soilborne diseases by these disease-suppressive crops, particularly for the control of *Rhizoctonia* (Cohen et al. 2005; Davis et al. 1996, 2004; Larkin and Griffin 2007; Mazzola et al. 2001). Thus, there may be additional benefits and uses of these crops even when biofumigation effects are not utilized to the fullest as a green manure.

Regardless of the positive benefits of green manures, a big drawback to their use, particularly in commercial production, is that they take land out of production, and while there are substantial costs involved in growing the green manure, they produce no direct economic return to offset those costs. Whereas most rotation crops can provide some return, green manures and cover crops provide no direct monetary return. Of course, if the beneficial effects on soil health and the subsequent cash crop are enough to offset their expense, and hopefully provide a net increased return as well, then green manures can be well worth their place in the production system. In warmer climates, these biofumigation crops are routinely used as a fall-only green manure following a traditional spring-summer crop (which does not involve replacing some other economic rotation crop). However, as indicated in our trial, as well as in previous trials and attempts, in which the biofumigation crop needs to be planted no later than August 1st to be effective, use as a fall-only green manure is extremely limited under our conditions in the northeastern US and Canada. Before using disease-suppressive crops as green manure, growers need to be reasonably sure that the benefits will be worthwhile. So, in this study we also conducted some economic analyses to better determine just how these crops and types of management practices affect the economic return of the production systems, and how to be able to best utilize these disease-suppressive crops in a potato production system.

As expected, the mustard blend used as green manure provided the greatest overall effects on disease reduction and potato yield increase. And even when all production costs of both the rotation crop and potato crop were taken into account, use of mustard blend as a green manure provided a substantial increase in the economic return of the system relative to using a standard barley rotation crop. In previous studies, McGuire (2003, 2012) observed that mustard green manures were an economical and effective replacement for chemical fumigation in potato production in the Pacific Northwest US. In Maine, Sexton et al. (2007) also determined that a mustard green rotation provided an economic boost (of~\$300/ha) over a standard barley rotation. In our study, from an economic perspective, use of a mustard green manure was not the most productive system. Because mustard blend, rapeseed, and sudangrass were also somewhat effective when grown as a harvestable rotation crop and then residues incorporated after harvest (and in some cases, even when residues were not incorporated), the most economically desirable combination was provided by mustard or rapeseed grown under HI management, providing an increase of more than \$800/ha over that provided by the standard barley rotation (HN). Mustard and rapeseed also increased profits when harvested and not incorporated (as with a standard rotation crop). Soybean grown as a harvested crop also provided good economic return, despite having generally negative effects on disease and yield, due to its cash crop value. However, because of the potential for disease and declining potato yield, soybean is not recommended in 2-year rotations with potato (Larkin and Honeycutt 2006; Larkin et al. 2010). Sudangrass, although provided positive returns, did not fair as well economically as the other disease-suppressive crops, despite positive effects on disease and yield, due to lower overall crop value and returns. Although no other studies have compared different management practices, in a comparison among existing rotations in Maine, DeFauw et al. (2012) also observed that soybean and rapeseed (canola) rotations provided increased economic returns over those of a standard barley rotation, that were similar to what were observed in our study.

In conclusion, this research has demonstrated that disease-suppressive crops, such as mustard, rapeseed, and sudangrass, grown as green manures, or as harvested rotation crops, can significantly reduce certain soilborne diseases, increase subsequent potato yield, and also provide an enhanced economic return relative to a standard small grain rotation crop. The mustard blend crop used was effective under all management practices, solidifying its effects as a disease-suppressive crop, even when not incorporated as a green manure. Also, all rotation crops grown as green manures provided disease and yield benefits compared to management as a cover crop, indicating the benefits of green manuring independent of biofumigation. Although the combination of a mustard blend rotation grown as a green manure provided the most substantial benefits to disease reduction and increased potato yield, based on economic returns, mustard or rapeseed grown as a harvestable cash crop and then the residues incorporated, provided the most productive and profitable management approach for using disease-suppressive crops in potato production. Thus, the message to growers is that, although green manures may provide the best overall results, use of a disease-suppressive rotation crop as a harvested crop can still provide positive benefits on soilborne disease and yield, and due to the additional income provided by the rotation crop harvest, may provide better economic returns overall. Regardless, it is clear that utilization of such disease-suppressive crops within potato cropping systems can provide highly beneficial and economically productive results, as well as potentially enhance sustainability of potato cropping systems through improved soil health, reductions in soilborne disease, and increased crop yield.

Acknowledgments We would like to thank our colleagues C.W. Honeycutt, T. Griffin, and M. Olanya for their involvement in the concept, planning and set-up of this study, L. Matthiesen for her thorough and capable technical assistance on all aspects of this work, D. Cowperthwaite for managing and maintaining the field site, and P. Pinette, G. Trusty, E. Champaco, J. Hunt, and B. LeGasse for additional technical support.

References

Abdallahi, M.M., and A. N'Dayegamiye. 2000. Effects of green manures on soil physical and biological properties and on wheat yields and N uptake. *Canadian Journal of Soil Science* 80: 81–89.

Amosson, S., L. Almas, D. Jones, and L. Guerrero. 2011. Texas crop and livestock enterprise budgets. Texas AgriLife Extension Center, TX, Vol. B-1241. Texas A&M AgriLife Extension.

Bernard, E., R.P. Larkin, S. Tavantzis, M.S. Erich, A. Alyokhin, and S. Gross. 2014. Rapeseed rotation, compost, and biocontrol amendments reduce soilborne diseases and increase tuber yield in organic and conventional potato production systems. *Plant and Soil* 374: 611–627.

Brown, P.D., and M.J. Morra. 1997. Control of soilborne plant pests using glucosinolate-containing plants. *Advances in Agronomy* 61: 167–231.

Carter, M.R., and J.B. Sanderson. 2001. Influence of conservation tillage and rotation length on potato productivity, tuber disease and soil quality parameters on a fine sandy loam in eastern Canada. *Soil and Tillage Research* 63: 1–13.

Chander, K., S. Goyal, M.C. Mundra, and K.K. Kapoor. 1997. Organic matter, microbial biomass and enzymatic activity of soils under different crop rotations in the tropics. *Biology and Fertility of Soils* 24: 306–310.

Cherr, C.J., J.M.S. Scholberg, and R. McSorley. 2006. Green manure approaches to crop production: a synthesis. *Agronomy Journal* 98: 302–319.

Cohen, M.F., M. Mazzola, and H. Yamasaki. 2005. *Brassica napus* seed meal soil amendment modifies microbial community structure, nitric oxide production and incidence of *Rhizoctonia* root rot. *Soil Biology & Biochemistry* 37: 1215–1227.

Collins, H.P., A.K. Alva, R.A. Boydston, R.L. Cochran, P.B. Hamm, A. McGuire, and E. Riga. 2006. Soil microbial, fungal, and nematode responses to soil fumigation and cover crops under potato production. *Biology and Fertility of Soils* 42: 247–257.

Cook, R.J. 1986. Interrelationships of plant health and the sustainability of agriculture, with special reference to plant diseases. *American Journal of Alternative Agriculture* 1: 19–24.

Cook, R.J. 2000. Advances in plant health management in the twentieth century. *Annual Review of Phytopathology* 38: 95–116.

Davis, J.R., O.C. Huisman, D.T. Westermann, S.L. Hafez, D.O. Everson, L.H. Sorensen, and A.T. Schneider. 1996. Effects of green manures on verticillium wilt of potato. *Phytopathology* 86: 444–453.

Davis, J.R., O.C. Huisman, D.T. Westermann, D.O. Everson, A. Schneider, and L.H. Sorensen. 2004. Some unique benefits with sudangrass for improved U.S.#1 yields and size of Russet Burbank potato. *American Journal of Potato Research* 81: 403–413.

Davis, J.R., O.C. Huisman, D.O. Everson, P. Nolte, L.H. Sorensen, and A.T. Schneider. 2010. Ecological relationships of Verticillium wilt suppression of potato by green manures. *American Journal of Potato Research* 87: 315–326.

DeFauw, S.L., R.P. Larkin, P.J. English, J.M. Halloran, and A.K. Hoshide. 2012. Geospatial evaluations of potato production systems in Maine. *American Journal of Potato Research* 89: 471–488.

Fageria, N.K. 2007. Green manuring in crop production. *Journal of Plant Nutrition* 30: 691–719.

Fageria, N.K., V.C. Baligar, and B.A. Bailey. 2005. Role of cover crops in improving soil and row crop productivity. *Communications in Soil Science and Plant Analysis* 36: 2733–2757.

Goyal, S., M.M. Mishra, I.S. Hooda, and R. Singh. 1992. Organic matter-microbial biomass relationships in field experiments under tropical conditions: effects of inorganic fertilizers and organic amendments. *Soil Biology and Biochemistry* 24: 1081–1084.

Goyal, S., K. Chandler, M.C. Mundra, and K.K. Kapoor. 1999. Influence of inorganic fertilizers and organic amendments on soil organic matter and soil microbial properties under tropical conditions. *Biology and Fertility of Soils* 29: 196–200.

Grandy, A.S., G.A. Porter, and M.S. Erich. 2002. Organic amendment and rotation crop effects on the recovery of soil organic matter and aggregation in potato cropping systems. *Soil Science Society of America Journal* 66: 1311–1319.

Halloran, J.M., T.S. Griffin, and C.W. Honeycutt. 2005. An economic analysis of potential rotation crops for Maine potato cropping systems. *American Journal of Potato Research* 82: 155–162.

Halloran, J.M., R.P. Larkin, and C.W. Honeycutt. 2008. The economic impacts of disease suppressive rotations in Maine potato cropping systems. *Crop Management (Online)*. doi:10.1094/CM-2008-0912-01-RS.

Halloran, J.M., R.P. Larkin, S.L. DeFauw, O.M. Olanya, and Z. He. 2013. Economic potential of compost amendment as an alternative to irrigation in Maine potato production systems. *American Journal of Plant Sciences* 4: 238–245.

Hide, G.A., and P.J. Read. 1991. Effects of rotation length, fungicide treatment of seed tubers and nematicide on diseases and the quality of potato tubers. *Annals of Applied Biology* 119: 77–87.

Hoekstra, O. 1989. Results of 24 years of crop rotation research at 'De Schreef' experimental site. In *Effects of crop rotation on potato production in the temperate zones*, ed. J. Vos, 37–43. Dordrecht: Kluwer Academic Publishers.

Honeycutt, C.W., W.M. Clapham, and S.S. Leach. 1996. Crop rotation and N fertilization effects on growth, yield, and disease incidence in potato. *American Potato Journal* 73: 45–61.

Kirkegaard, J.A., P.A. Gardner, D.M. Desmarchelier, and J.F. Angus. 1993. Biofumigation—using Brassica species to control pests and diseases in horticulture and agriculture. In *1st Australasian soil-borne disease symposium*, ed. R.C. Margery, 155–157. Brisbane: Bureau of Sugar Experiment Station.

Krupinsky, J.M., K.L. Bailey, M.M. McMullen, B.D. Gossen, and T.K. Turkington. 2002. Managing plant disease risk in diversified cropping systems. *Agronomy Journal* 94: 198–209.

Larkin, R.P., and T.S. Griffin. 2007. Control of soilborne diseases of potato using *Brassica* green manures. *Crop Protection* 26: 1067–1077.

Larkin, R.P., and C.W. Honeycutt. 2006. Effects of different 3-year cropping systems on soil microbial communities and Rhizoctonia diseases of potato. *Phytopathology* 96: 68–79.

Larkin, R.P., T.S. Griffin, and C.W. Honeycutt. 2010. Rotation and cover crop effects on soilborne potato diseases, tuber yield, and soil microbial communities. *Plant Disease* 94: 1491–1502.

Larkin, R.P., C.W. Honeycutt, and O.M. Olanya. 2011a. Management of Verticillium wilt of potato with disease-suppressive green manures and as affected by previous cropping history. *Plant Disease* 95: 568–576.

Larkin, R.P., C.W. Honeycutt, T.S. Griffin, O.M. Olanya, J.M. Halloran, and Z. He. 2011b. Effects of different potato cropping system approaches and water management on soilborne diseases and soil microbial communities. *Phytopathology* 101: 58–67.

Larkin, R.P., C.W. Honeycutt, O.M. Olanya, J.M. Halloran, and Z. He. 2012. Impacts of crop rotation and irrigation on soilborne diseases and soil microbial communities. In *Sustainable potato production: global case studies*, ed. Z. He, R.P. Larkin, and C.W. Honeycutt, 23–41. Dordrecht: Springer.

Little, S.A., P.J. Hocking, and R.S.B. Greene. 2004. A preliminary study of the role of cover crops in improving soil fertility and yield for potato production. *Communications in Soil Science and Plant Analysis* 35: 471–494.

Liu, G., Z. Li, H. Jing, X. Ye, H. Shi, Y. Wang, C. Yang, and D. Chang. 2010. Effects of consecutive turnover of green manures on soil microbial biomass and enzyme activity. *Plant Nutrition and Fertilizer Science* 16: 1472–1478.

MacRae, R.J., and G.R. Mehuys. 1985. The effect of green manuring on the physical properties of temperate-area soils. *Advances in Soil Science* 3: 71–94.

Magdoff, F. 2000. Concepts, components, and strategies of soil health in agroecosystems. *Journal of Nematology* 33: 169–172.

Magdoff, F., and H. van Es. 2009. Cover crops and crop rotations. In *Building soils for better crops*, 101–128. Waldorf: Sustainable Agriculture Reserach and Education Program.

Matthiessen, J.N., and J.A. Kirkegaard. 2006. Biofumigation and enhanced biodegradation: opportunity and challenge in soilborne pest and disease management. *Critical Reviews in Plant Sciences* 25: 235–265.

Mazzola, M., D.M. Granatstein, D.C. Elfving, and K. Mullinix. 2001. Suppression of specific apple root pathogens by *Brassica napus* seed meal amendment regardless of glucosinolate content. *Phytopathology* 91: 673–679.

McGuire, A.M. 2003. Mustard green manures replace fumigant and improve infiltration in potato cropping system. *Crop Management (Online)*. doi:10.1094/CM-2003-0822-01-RS.

McGuire, A.M. 2012. Mustard green manure use in eastern Washington state. In *Sustainable potato production: global case studies*, ed. Z. He, R.P. Larkin, and C.W. Honeycutt, 117–130. Dordrecht: Springer.

Olsen, K.D. 2003. *Farm management: principles and strategy*. New York: Wiley & Sons.

Ontario Ministry of Agriculture, Food, and Rural Affairs. 2013. *2013 Field crop budgets*, ed. Northern Ontario Regional Office, Publication 60. Ontario: Ministry of Agriculture, Food, and Rural Affairs.

Peters, R.D., A.V. Sturz, M.R. Carter, and J.B. Sanderson. 2003. Developing disease-suppressive soils through crop rotation and tillage management practices. *Soil and Tillage Research* 72: 181–192.

Peters, R.D., A.V. Sturz, M.R. Carter, and J.B. Sanderson. 2004. Influence of crop rotation and conservation tillage practices on the severity of soil-borne potato diseases in temperate humid agriculture. *Canadian Journal of Soil Science* 84: 397–402.

Powelson, M.L., K.L. Johnson, and R.C. Rowe. 1993. Management of diseases caused by soilborne pathogens. In *Potato health management*, ed. R.C. Rowe, 178. St. Paul: APS Press.

Sarrantonio, M., and E. Gallandt. 2003. The role of cover crops in North American cropping systems. *Journal of Crop Production* 8: 53–74.

Sarwar, M., J.A. Kirkegaard, P.T.W. Wong, and J.M. Desmarchelier. 1998. Biofumigation potential of Brassicas. III. In vitro toxicity of isothiocyanates to soil-borne fungal pathogens. *Plant and Soil* 210: 103–112.

Scholte, K. 1987. The effect of crop rotation and granular nematicides on the incidence of *Rhizoctonia solani* in potato. *Potato Research* 30: 187–199.

Secor, G.A., and N.C. Gudmestad. 1999. Managing fungal diseases of potato. *Canadian Journal of Plant Pathology* 21: 213–221.

Sexton, P., A.B. Plant, S.B. Johnson, and J. Jemison. 2007. Effect of a mustard green manure on potato yield and disease incidence in a rainfed environment. *Crop Management (Online)*. doi:10.1094/CM-2007-0122-02-RS.

Smolinska, U., and M. Horbowicz. 1999. Fungicidal activity of volatiles from selected cruciferous plants against resting propagules of soil-borne fungal pathogens. *Journal of Phytopathology* 147: 119–124.

Specht, L.P., and S.S. Leach. 1987. Effects of crop rotation on Rhizoctonia disease of white potato. *Plant Disease* 71: 433–437.

Stark, C., L.M. Condron, A. Stweart, H.J. Di, and M. O'Callaghan. 2007. Influence of organic and mineral amendments on microbial soil properties and properties. *Applied Soil Ecology* 35: 79–93.

Stevenson, W.R., R. Loria, G.D. Franc, and D.P. Weingartner. 2001. *Compendium of potato diseases*, 2nd ed. St. Paul: American Phytopathological Society.

Thorup-Kristensen, K., J. Magid, and L.S. Jensen. 2003. Catch crops and green manures as biological tools in nitrogen management in temperate zones. *Advances in Agronomy* 79: 227–302.

USDA, and NASS. 2010. Annual Bulletin, New England Agriculture Statistics, pp. 160. United States Department of Agriculture.

USDA, and NASS. 2013. Statistics by Subject [Online] www.usda.gov/Statistics_by_Subject/ (verified September 2013).