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ORIGINAL ARTICLE

Effect of green manure and supplemental fertility amendments on selected soil quality parameters in an organic potato rotation in Eastern Canada

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Abstract The effects of green manure, crop sequence and off-farm composts on selected soil quality parameters were assessed in a three-year organic potato (*Solanum tuberosum* L.) rotation in Eastern Canada. Three crop sequences varying in preceding green manure [red clover (RCl) + RCl, and beans/buckwheat or carrots + oats/peas/vetch mixture (OPV)] as main plots and four fertility treatments applied in the potato phase only [control; inorganic fertilizer; municipal solid waste compost (MSW); composted paper mill biosolid (PMB)] as subplots were compared. In 2008 and 2010, changes in selected soil quality parameters (0–15 cm) were assessed prior to planting of potatoes and at potato tuber initiation stage. Potentially mineralizable nitrogen (N) and the acid phosphatase enzyme activity average values across years were greater following RCl (1.51 abs and 622 kg ha^{-1}) compared with OPV (1.32 abs and 414 kg ha^{-1}) at potato planting. Soil NO_3–N average value was greater following RCl compared with OPV (63 vs. 52 kg ha^{-1}) at tuber initiation. For the other measured parameters, OPV and RCl were similar. The soil organic carbon (C) and particulate organic matter-C were greater under PMB and MSW (31.1 and 7.57 kg ha^{-1}) compared with fertilizer treatment (27.9 and 6.05 kg ha^{-1}). The microbial biomass C and microbial biomass quotient were greater under MSW (216 kg ha^{-1} and 0.73 %) than PMB and fertilizer (147 kg ha^{-1} and 0.50 %) across crop rotations. Annual legume green manures and off-farm composts can be used to satisfy potato N requirement and maintains soil quality in organic potato rotations.

Keywords Legume green manure · Municipal solid waste · Papermills biosolid · Organic potato · Soil quality

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Introduction

Practices common to certified organic production have become increasingly common in intensive potato (*Solanum tuberosum* L.) cropping systems in the recent years. The benefits of extended rotations including cover crops and green manure (Angers et al. 1999; Nelson et al. 2009) and the application of organic amendments (Fahmy et al. 2010) in potato production are well recognized. However, limited information is available on effects of compost and green manure combination, and replacing biennial green manure species with a combination of a low demand crop and an annual green manure on soil quality parameters under organic potato production.

Leguminous green manures contribute to carbon (C) and N inputs to the soil, thus improving soil quality and fertility (Zotarelli et al. 2012). Legumes can increase N availability to subsequent potato crops and improve soil physical properties. They contain large quantities of N most of which is released during the first year after incorporation (Sharifi et al. 2008; Lynch et al. 2012). Extended rotations including leguminous green manures under commercial organic potato farms in Atlantic Canada retained soil organic matter (SOM) and allowed recovery of microbial biomass C (MBC) following the potato phase (Nelson et al. 2009).

Municipal solid waste (MSW) compost, currently used in agriculture as a soil conditioner and source of nutrients for crops, increases SOM levels and soil pH (Rodd et al. 2001; Weber et al. 2014), improves soil structure and can result in low soil bulk density (BD). Studies have shown that addition of MSW compost to the soil improves the water holding capacity and increases the soil aggregate stability (Annabi et al. 2007). In a long-term experiment, multiple additions of MSW compost at rate 20 and 80 Mg ha^{-1} increased MBC, and this increase persisted 8 years after application (Garcia-Gil et al. 2000). The MSW compost tends to have low N content and applications tailored to meet N requirements may result in a buildup of soil P (Mkhabela and Warman 2005).

Raw or fresh primary/secondary paper mill biosolids (PMB) can be effective in agronomic and nursery crop production. These materials improve the physical, chemical, and biological soil properties, buildup SOM, and provide essential major crop nutrients (N, P, K, Ca, Mg, and S) (Brauer and Aiken 2006; Sciubba et al. 2014). Well processed, PMB compost presents no phytotoxic effects due to very low to non-detectable heavy metal content when applied across a range of crop species (Price and Voroney 2007). High C content and noticeable amounts of P encourage the use of PMB as supplemental source of organic matter and P in potato production systems (Fahmy et al. 2010).

To date, the majority of studies conducted on potato-based 3-year rotation systems that include legume green manure in Nova Scotia and the other Atlantic provinces of Eastern Canada have only focused on biennial species [i.e. red clover (RCl) (*Trifolium pratense*)] that persist throughout the 2-year green manure phase of the rotation (Lynch et al. 2012). Thus, it is not clear whether the introduction of an annual legume green manure (Lynch et al. 2012) in combination with an annual low nutrient demand cash crop affect the soil quality and consequently long-term productivity. In addition, few studies have explored the interaction effects of different green manures (Carter et al. 2009; Fahmy et al. 2010) and off-farm composts (Mkhabela and Warman 2005; Hargreaves et al. 2008; Gagnon and Ziadi 2012) on soil quality parameters. We hypothesize that, the introduction of annual cash crop with low nutrient demand (during the first year of the rotation) and annual legume green manure (during the second year of the rotation) will have similar effects on selected soil quality parameters compared with conventional potato-based 3-year rotation systems with a biennial legume green manure phase. We also hypothesize that a combination of green manure and off-farm bio-waste compost can improve the soil quality parameters and N cycling, and produce comparable yields with fertilized treatment. The objective of this study was to assess the effects of management practices consisting of annual cash crop and annual legume green manure and off-farm bio-waste composts applied to the potato phase of a potato-based 3-year rotation system on physical, biological, and chemical soil properties corresponding to overall soil quality.

Materials and methods

Site description and experimental design

The organic vegetable rotation experiment (2006–2010) was established on a Pugwash sandy loam [Cryorthods under the U.S. Soil Taxonomy (Soil Survey Staff 2010)] located at the Dalhousie Faculty of Agriculture experimental site (formerly Nova Scotia Agricultural College) in Truro, Nova Scotia, Canada (45°23′ N, 63°14′ W). Before 2006, the soil was cropped with maize (*Zea mays*) under reduced tillage management for 4 years following a long history of forage production. Average pH_{water} was 6.3 with 631 g kg^{-1} sand and 156 g kg^{-1} clay (pipette method). The average temperature during the growing season (May–October) is 14.0 °C with 597 mm of total precipitation. Compared with 30 years

Table 1 Monthly total precipitation and mean monthly air temperatures at Debert, Nova Scotia in 2008 and 2010 in comparison with the long-term (1971–2000) average (http://climate.weather.gc.ca/climate_normals/results_e.html)

Month	Precipitation (mm)				Air temperature (°C)		
	2008	2010	30-year average		2008	2010	30-year average
May	103	29	103		9.1	7.8	10.2
June	58	207	96		15.6	14.5	15.1
July	78	122	91		19.9	19.8	18.6
August	168	68	90		17.8	18.5	18.2
September	145	97	109		13.9	15.8	13.7
October	88	145	108		7.8	8.2	8.0
Sum	640	668	597	Average	14.0	14.1	14.0

normal precipitation, the potato phase years of 2008 and 2010 were rainy years (Table 1). In 2008, the majority of precipitation occurred in August and September, while in 2010 June and July had above normal precipitation. The average monthly temperatures in 2008 and 2010 were within ± 1.5 °C of the 30-year normal mean monthly temperatures.

The experimental design was a split-plot with three replicates. Three potato-based 3-year rotation systems including various green manures and cash crops with low nutrient demand were applied to main plots and four fertility treatments were assigned to subplots. The green manures tested were RCl and vetch (V) (*Vicia villosa* L.); the cash crops with low nutrient demand were beans (B) (*Phaseolus lunatus* L.) and carrot (*Daucus carrota* subsp. sativus). Other plants included in the green manure phases of the rotations were oats (O) (*Avena sativa* L.), buckwheat (Bu) (*Polygonum convolvulus* L.), and pea (P) (*Pisum sativum* L.). The three potato-based 3-year rotations were combined as follows: C1 (conventional), O underseeded with RCl (ORCl) (1st year)—RCl (2nd year)—Potato (3rd year); C2, carrots (1st year)—OPV (Oats/Pea/Vetch) mixture (2nd year)—Potato (3rd year); and C3, B followed by Bu (1st year)—OPV mixture (2nd year)—Potato (3rd year). The main plots were divided into two parts such that two cycles of each potato-based 3-year rotations were obtained in 2006–2008 and 2008–2010 (Table 2). The fertility treatments were only applied to the potato phase of the rotation and included (1) CONT (control), non-fertilized and non-amended; (2) FERT, fertilized with mineral N and P at recommended rates based on regional N credits for leguminous green manures and soil test Mehlich-3 P (P_{M3}); (3) MSW source separated compost (12 Mg ha^{-1} wet weight; dry weight = 60 %); and (4) PMB compost (30 Mg ha^{-1} wet weight; dry weight = 39 %). Individual sub-plot size was 14 × 2.5 m.

Table 2 Representation of the three potato-based 3-year rotation systems at Dalhousie Faculty of Agriculture experimental site (formerly Nova Scotia Agricultural College) in Truro, Nova Scotia, Canada

Rotation	Plot#	Year				
		2006	2007	2008	2009	2010
C1	1a	ORCl	Carrot	ORCl	RCl	Potato
C1	1b	ORCl	RCl	Potato	ORCl	Carrot
C3	8a	ORCl	Carrot	BBu	OPV	Potato
C3	8b	BBu	OPV	Potato	ORCl	Carrot
C2	10a	ORCl	BBu	Carrot	OPV	Potato
C2	10b	Carrot	OPV	Potato	ORCl	BBu
C1	14a	ORCl	Carrot	ORCl	RCl	Potato
C1	14b	ORCl	RCl	Potato	ORCl	Carrot
C2	17a	Carrot	OPV	Potato	ORCl	BBu
C2	17b	ORCl	BBu	Carrot	OPV	Potato
C3	22a	BBu	OPV	Potato	ORCl	Carrot
C3	22b	ORCl	Carrot	BBu	OPV	Potato
C2	28a	Carrot	OPV	Potato	ORCl	BBu
C2	28b	ORCl	BBu	Carrot	OPV	Potato
C3	31a	ORCl	Carrot	BBu	OPV	Potato
C3	31b	BBu	OPV	Potato	ORCl	Carrot
C1	34a	ORCl	RCl	Potato	ORCl	Carrot
C1	34b	ORCl	Carrot	ORCl	RCl	Potato

ORCl, Oats (*Avena sativa* L.) underseeded with Red clover (*Trifolium pratense* L.); Potato (*Solanum tuberosum* L.); Carrot (*Daucus carota* subsp. sativus); OPV, Oats/Pea (*Pisum sativum* L.)/Vetch (*Vicia villosa* L.) mixture; BBu, Beans (*Phaseolus lunatus* L.) followed by Buckwheat (*Polygonum convolvulus* L.); a, first part of the main plot used for the rotation cycle 2006–2008; b, second part of the main plot used for the rotation cycle 2008–2010

Table 3 The average chemical characteristics of source separated municipal solid food waste compost (MSW) and composted paper mill biosolids (PMB)

Properties	Unit	MSW	PMB
Dry matter	%	59.9 (1.67)[a]	38.8 (1.82)
pH	–	7.47 (0.09)	6.63 (0.54)
TOC	%	14.7 (0.63)	23.1 (0.53)
TON	%	2.09 (0.09)	1.62 (0.02)
C/N ratio	–	7.00	14.30
NH_4–N	%	0.11 (0.00)	0.16 (0.01)
Ca	%	3.54 (0.04)	0.99 (0.02)
P	%	0.58 (0.00)	0.34 (0.00)
K	%	0.55 (0.01)	0.15 (0.02)
Mg	%	0.46 (0.02)	0.13 (0.01)
Na	%	0.17 (0.01)	0.04 (0.00)
Fe	ppm	16,639 (725)	7,080 (710)
Mn	ppm	1,528 (60)	1,079 (16)
Cu	ppm	32.2 (2.07)	23.1 (0.25)
Zn	ppm	271 (19.7)	121 (1.57)
B	ppm	24.3 (0.44)	17.7 (0.61)

[a] Values in parenthesis represent standard deviations of the means (n = 3)

Both MSW and PMB composts met compost quality criteria set by the Canadian Council of Ministers of the Environment (2005) regarding heavy metal and pathogen content specified under the Canadian Organic Standards (Canadian General Standards Board 2011). The average values for chemical composition of composts are reported in Table 3. Composts were manually applied in mid-May and hills and furrows were formed approximately 4 weeks after planting using a tool carrier. Compost rates were designed to provide the potato crop with a current-season average of 60 kg ha^{-1} of plant available P in form of P_2O_5 based on the compost analysis results, assuming 50 % of the applied total P in compost is plant available in the year of application. The compost application also provided on average 82 and 121 kg total N ha^{-1} $year^{-1}$ for MSW and PMB, respectively. The FERT treatment consisted of a mixture of 80 kg N ha^{-1} as ammonium nitrate and 60 kg P_2O_5 ha^{-1} as triple super phosphate. The regional N credit estimation for soild stand of red clover is 50 kg N ha^{-1} (Zebarth et al. 2007). Nitrogen and P fertilizers were banded 5 cm below and 5 cm to the side of the seed at planting. Potassium (K) was broadcast each year on all plots as Sulpomag (0-0-22) based on soil analysis.

The seeding rates for the rotation crops were 70 kg ha^{-1} for oats (cv. AC Francis), 12 kg ha^{-1} for RCl (cv. AC Christie), 3.20 kg ha^{-1} for carrots (cv. Maverick), 60, 60, and 34 kg ha^{-1} for oats, pea (cv. Mozart), and common vetch, respectively in OPV mixture, and 108 kg ha^{-1} for beans (cv. Goldrush). Oats were mowed late in the season before seed maturity using a flail mower and the RCl was then allowed to grow until late autumn. The RCl plots that were going to potatoes were moldboard plowed (10–12 cm depth) late in the previous autumn. Bean residues were diced and plowed in late July to early August, and Bu was seeded and allowed to grow until mid-October then incorporated. The OPV phase of the rotation preceding potato was treated as green manure and incorporated by discing late in the autumn. Potato was planted by hand early in June using hand-cut seed ($\approx 50 \pm 3$ g each) of cultivar Goldrush. Seed pieces were planted in rows 83 cm apart, at 31 cm within-row spacing and at a depth of 5–10 cm.

Weeds were controlled by mechanical cultivation before tuber initiation stage and by hand pulling thereafter. Late blight (*Phytophthora infestans*) and Colorado potato beetle (*Leptinotarsa decemlineata*) were controlled with the application of copper hydroxide (Parasol) and Entrust®, respectively, as required. No supplemental irrigation was applied.

Composite soil samples (eight subsamples per plot) were randomly collected at 0–15 cm depth using an auger (2.5 cm diameter) in 2008 and 2010 at potato planting and tuber initiation stage [$\sim$35 days after planting (DAP)]. The field moist soil samples were homogenized, sieved (<2 mm), and kept in the cooler at 4 °C until analysis. In addition, bulk densities were measured as described by Blake and Hartge (1986) using soil cores collected in each plot at each sampling date.

Soil physical analysis

The SOC and SON were measured by dry combustion using a LECO CNS-1000 analyzer (LECO Corporation, St. Joseph, MI, USA). Particulate organic matter (POM) was determined by dispersing and washing a 25 g moist soil sample through a 53 µm sieve (Gregorich and Beare 2007). Retained sand and macroorganic matter were air-dried and weighed and C and N concentrations determined on each fraction by dry combustion. The masses of C and N per gram of air-dried soil were calculated as POM-C and POM-N, respectively and the POM-C/POM-N ratio was calculated as an indicator of POM quality.

Soil biological analysis

MBC was determined using the chloroform fumigation-extraction method (Voroney et al. 2007): two subsamples (25 g) of field moist soil were placed into 100 mL glass vials. One sample was placed into a vacuum desiccator for 24 h and the other subsample (control) was left unfumigated. Soluble C was immediately extracted from the unfumigated controls with 75 mL of 0.5 M potassium sulphate (K_2SO_4) (1:3, soil:solution ratio), shaken for 1 h (Eberbach 6000 bench top shaker) and filtered using glass fiber filter paper. Following the 24 h fumigation period, residual chloroform was removed by vacuum and soluble C extracted as described above. The filtrate was frozen at −4 °C until further analysis. An aliquot of the K_2SO_4 extract was analyzed for dissolved organic C by automated persulfate digestion and subsequent colorimetric detection of CO_2 using Technicon AutoAnalyzer III (Technicon Instruments Corporation, Tarrytown, NY). The MBC was calculated as the difference in soluble C between fumigated and non-fumigated samples with K_{EC} factor 0.35 (Voroney et al. 2007). The MBC/SOC ratio (*q*MBC) was calculated as an indicator of the quality of MBC.

The ultraviolet absorbance of the 0.01 *M* $NaHCO_3$ extract at 205 and 260 nm ($NaHCO_3$-205 and $NaHCO_3$-260) was determined as an indicator of potentially mineralizable N as described by Sharifi et al. (2007). Briefly, 2.5 g of air-dried soils were shaken in 50 ml of 0.01 M $NaHCO_3$ for 15 min. The suspension was filtered through glass fiber filter paper and the ultraviolet absorbance of the extract was measured at 205 and 260 nm with an ultraviolet spectrometer (Jenway® 6505 UV/Vis Spectrophotometers).

The activities of acid phosphatases (APA) were assayed by the methods of Tabatabai (1994). The procedure involves extraction and quantitative determination of μg p-nitrophenol released when moist soil is incubated with p-nitrophenyl phosphate in modified universal buffer adjusted to pH 6.5. Enzyme activity was assayed on >2 mm field-moist pre-plant and tuber initiation soil samples.

Soil chemical analysis

The P_{M3} was determined prior to planting and at tuber initiation using a Varian 725-ES Radial ICP-OES after extracting the air-dried soil with Mehlich-3 solution (Ziadi and Tran 2008). Soil mineral N was measured using K_2SO_4 extraction of moist soil samples. At analysis, the gravimetric moisture content of a 20 g subsample was determined. A 25 g subsample of fresh soil was extracted with 0.5 *M* K_2SO_4 using a 1:3 (w:v) soil:extractant ratio. After shaking for 1 h and filtering through glass fiber filter paper, the soil mineral NO_3–N and NH_4–N concentrations were determined colorimetrically on a Technicon TRAACS II (Technicon Industrial Systems Corp., Tarrytown, New York) as described by Burton et al. (2008).

Statistical analysis

All data were tested for normality using the SAS univariate procedure. Analyses of variance (ANOVA) for parameters measured on pre-plant soils were performed using the Proc Mixed of SAS, version 9.3 (SAS Institute 2010) with Replicates as random effect, Year as repeated effect, and Rotation and Rotation × Year as fixed effect. Differences among least square means (LSMEANS) for all treatment pairs were tested at a significance level of $P = 0.05$. The ANOVA for parameters measured on soil sampled at tuber initiation were performed using the Proc Mixed of SAS with Replicates as random effect, Year as repeated effect, and Rotation, Amendment and the 2- and 3-way interactions as fixed effects. Differences among least square means (LSMEANS) for all treatment pairs were tested at a significance level of $P = 0.05$. Where appropriate, means were compared with a combination of orthogonal and polynomial contrasts: CONT versus (FERT, MSW, PMB); FERT versus (MSW, PMB); MSW versus PMB.

Results and discussion

Characteristics of organic amendments

The chemical composition of MSW and PMB composts used in this study differed greatly, but were typical of averages reported in North America (Edwards and Someshwar 2000). The MSW had a pH of 7.47 and a greater dry matter content compared with PMB compost. The MSW compost had a lower C

Table 4 Selected soil physical, biological and chemical indicators following different green manure types and crop sequences prior to potato plantation in an organic potato rotation in Truro, Nova Scotia, Canada

	Physical				Biological			Chemical			
	BD g cm^{-3}	SOC Mg ha^{-1}	SON	C/N –	$NaHCO_3$-205 abs	$NaHCO_3$-260	APA kg ha^{-1}	pH –	P_{M3} kg ha^{-1}	NO_3–N	NH_4–N
Least square means											
Rotation (Rot)											
C1	1.05a	28.4a	2.54a	10.7a	1.51a	0.56a	622a	5.92a	339a	82.3a	2.07a
C2	1.19a	30.0a	2.46a	12.1a	1.30b	0.54a	416b	6.40a	324a	62.2a	0.76a
C3	1.11a	29.7a	2.40a	12.6a	1.34b	0.56a	412b	6.08a	307a	67.2a	1.20a
Year											
2008	1.10A	28.7A	2.11B	13.3A	1.26B	0.55A	436A	6.17A	354A	98.6A	2.18A
2010	1.13A	30.1A	2.83A	10.4B	1.50A	0.55A	530A	6.10A	334B	42.6B	0.51A
Sources of variation					*P* values						
Rot	0.089	0.553	0.742	0.155	0.028	0.495	0.006	0.152	0.678	0.073	0.541
Year	0.450	0.447	0.002	0.011	0.014	0.953	0.317	0.655	0.017	<0.001	0.094
Rot × Year	0.191	0.158	0.258	0.630	0.644	0.265	0.491	0.323	0.998	0.089	0.291

BD, bulk density; SOC, soil organic carbon; SON, soil organic nitrogen; C/N, carbon to nitrogen ratio; $NaHCO_3$-205, $NaHCO_3$-260, potentially mineralizable N measured using the 0.01 M $NaHCO_3$ extract at wave length 205 and 260 nm, respectively; APA, alkaline phosphatase activity; P_{M3}, Mehlich-3 extractable phosphorus; NO_3–N, soil nitrate; NH_4–N, soil ammonium; Means followed by the same lower or capital letter in each column are not significantly different at $P = 0.05$

Table 5 Least square means and analysis of variance of selected soil physical, biological and chemical indicators in a potato field following different green manure types and crop sequences and amendment application at tuber initiation in an organic potato rotation in Truro, Nova Scotia, Canada

	Physical								Biological			Chemical		
	SOC Mg ha^{-1}	SON	C/N –	POM-C Mg ha^{-1}	POM-N	POM-C/POM-N –	POM-C/SOC %	POM-N/SON	APA kg ha^{-1}	MBC	*q*MBC %	P_{M3} kg ha^{-1}	NO_3–N	NH_4–N
Least square means														
Rotation (Rot)														
C1	30.7a	2.48a	12.6a	6.57a	0.92a	8.80a	22.0a	41.3a	1,000a	186a	0.62a	342a	63.1a	2.55a
C2	29.7a	2.80a	10.9a	6.15a	0.77a	9.37a	20.4a	28.6a	852a	157a	0.52a	327a	49.2b	1.96a
C3	29.2a	2.47a	12.6a	6.95a	0.85a	10.45a	23.7a	37.0a	844a	174a	0.64a	291a	54.2b	1.92a
Amendment (Amend)														
Control (Cont)	29.3	2.47	12.0	5.05	0.65	9.86	18.3	30.1	797	181	0.64	315	51.5	2.42
Fertilizer (FERT)	27.9	2.55	11.6	6.05	0.84	10.15	21.6	35.3	1,005	151	0.54	323	58.9	2.24
Municipal solid waste (MSW)	29.6	2.80	11.3	6.70	0.80	9.50	22.7	32.4	894	216	0.73	320	57.4	1.80
Paper mills biosolids (PMB)	32.6	2.51	13.4	8.44	1.09	8.65	25.5	44.8	899	142	0.45	323	54.2	2.13
Year														
2008	28.1B	2.15B	12.8A	6.03A	0.86A	6.92B	21.7A	41.5A	1341A	184A	0.67A	357A	65.9A	2.14A
2010	31.6A	3.02A	11.3A	7.08A	0.83A	12.16A	22.4A	29.8B	457B	161A	0.51B	323B	45.1B	2.15A
Sources of variation						*P* values								
Rot	0.302	0.151	0.445	0.320	0.822	0.249	0.135	0.231	0.272	0.428	0.311	0.096	0.017	0.123
Amend	0.003	0.449	0.623	<0.001	0.458	0.531	0.007	0.355	0.441	0.025	0.058	0.988	0.513	0.454
Rot × Amend	0.589	0.899	0.904	0.071	0.916	0.093	0.307	0.874	0.659	0.606	0.830	0.869	0.671	0.090
Year	0.001	0.001	0.202	0.088	0.887	0.001	0.684	0.045	<0.001	0.185	0.012	<0.001	<0.001	0.993
Rot × Year	0.774	0.451	0.212	0.557	0.964	0.662	0.714	0.838	0.206	0.389	0.551	0.555	0.317	0.270
Amend × Year	0.112	0.757	0.826	0.025	0.110	0.520	0.183	0.099	0.458	0.897	0.565	0.419	0.372	0.133
Rot x Amend × Year	0.928	0.986	0.965	0.975	0.240	0.503	0.913	0.365	0.500	0.128	0.197	0.941	0.993	0.107
Selected contrasts														
Cont vs. Fert, MSW, PMB	0.389	0.389	0.929	0.001	0.263	0.661	0.004	0.297	0.200	0.614	0.470	0.735	0.227	0.258
FERT versus MSW, PMB	0.003	0.567	0.605	0.007	0.659	0.265	0.120	0.654	0.314	0.208	0.570	0.970	0.507	0.404
MSW versus PMB	0.016	0.210	0.231	0.007	0.307	0.438	0.144	0.164	0.968	0.006	0.010	0.928	0.551	0.382

SOC, soil organic carbon; SON, soil organic nitrogen; C/N, carbon to nitrogen ratio; POM-C, particulate organic matter associated carbon; POM-N, particulate organic matter associated nitrogen; POM-C/POM-N, particulate organic matter associated carbon to particulate organic matter associated nitrogen ratio; APA, alkaline phosphatase activity; MBC, microbial biomass carbon; *q*MBC, microbial biomass carbon to soil organic carbon ratio; P_{M3}, Mehlich-3 extractable phosphorus; NO_3–N, soil nitrate; NH_4–N, soil ammonium; Means followed by the same lower or capital letter for the letter in each column are not significantly different at $P = 0.05$

content and C/N ratio, but a greater N content compare with PMB compost. The C/N ratio of both compost materials was lower than that used by Gagnon and Ziadi (2012), but was within the range of that used by Ziadi et al. (2013). In addition, the C/N ratio of both materials was below critical values of 20–30 defined by Sims (1990) and suggested net N mineralization. The MSW compost had lower NH_4–N content, but higher Ca, P, K, Mg, and Na content compare with PMB compost. The N and P contents of the materials, even though low, indicate the possibility of using them as a supplemental source of nutrients in organic potato production systems. The C/P ratio was 25.3 for MSW and 67.3 for PMB. These C/P ratios were lower than 200 indicating that a net mineralization of organic P would occur during the early stage of material decomposition after its addition to the soil (Havlin et al. 1999). The proportion of Ca and the pH, particularly that of MSW, indicates that this material could be used as well as calcium amendment to raise soil pH or correct soil acidity. In addition, the MSW compost had higher Fe, Mn, Cu, Zn, and B concentrations compare with PMB compost.

Soil physical properties

Prior to potato plantation, the soil BD, SOC, SON, and C/N ratio did not vary among the three rotation systems (Table 4). Some inter-annual (2008 vs. 2010) variability was observed for SON and C/N ratio, but the extent was not affected by the rotation systems.

At potato tuber initiation, the most consistent effects of fertility treatments on soil physical properties were observed on SOC, POM-C, and POM-C/SOC (Table 5). No significant interaction effects were found between treatments on soil physical properties except for POM-C. The compost treatments, MSW and PMB, as expected, significantly increased the SOC and POM-C compared with FERT treatment. In addition, the SOC also decreased with the FERT treatment compared with the CONT treatment. The low SOC observed following FERT treatment was probably caused by a greater decomposition of crop residues and SOM (Mulvaney et al. 2009).

Gagnon and Ziadi (2012) in a long-term experiment in Quebec, Canada found that applications of 30 and 60 Mg ha^{-1} PMB increased SOC by 4 and 8 g kg^{-1} over the control, respectively. In contrary, Crecchio et al. (2004) found that addition of MSW in a 6-year sugar beet (*Beta vulgaris*) and durum wheat (*Triticum turgidum*) rotation system increased the SOC from 13.3 to 15.0 g kg^{-1} soil. The absence of SOC change with MSW application compared with Crecchio et al. (2004) is probably due to the relative short period of compost application to this three-year potato-based rotation. The higher SOC and POM-C following application of PMB compared with MSW could be partly explained by the C content and C/N ratio of these compost materials (Table 3). In addition, the PMB amended soils generally have short wood fibers and kaolin clays derived from PMB amendments that progressively densify upon decay (Chantigny et al. 1999).

Crecchio et al. (2004) found that addition of composted MSW over 6 years increased the SON from 1.55 to 1.65 g kg^{-1} soil corresponding to an increase of 0.1 g kg^{-1} soil. On a loamy sand soil cropped with 3 years triticale (X *Triticosecale*) monoculture as test plant, SON was 0.68 g kg^{-1} under MSW amended soil, 0.46 g kg^{-1} under fertilized soil, and 0.50 g kg^{-1} under control corresponding to an increase of 0.22 and 0.17 g kg^{-1} compared with fertilized and control soils, respectively (Weber et al. 2007). Input of off-farm composted materials leads to increases in SON due to their TON content (Fahmy et al. 2010; Gagnon and Ziadi 2012). However, the small (and non significant) change in magnitude of SON with application of MSW or PMB observed in our study compared to other studies is probably due to the relative short period of application.

Soil biological properties

The potentially mineralizable N estimated using the $NaHCO_3$-205 method prior to potato plantation was significantly greater under C1 compared with C2 and C3 ($P = 0.028$) (Table 4). The value of the potentially mineralizable N at wave length 205 nm varied between 1.30 abs under C2 and 1.51 abs under C1. The APA was significantly influenced by the rotations ($P = 0.006$) and varied between 622 kg ha^{-1} under C1 to 416 kg ha^{-1} under C2 and 412 kg ha^{-1} under C3 rotations. The greater potentially mineralizable N and APA under C1 compared to C2 and C3 rotations can be explained by the occurrence of RCl persisting throughout the 2 years preceding potato plantation. No significant interaction effects were found between year and other treatments on soil biological properties.

Red clover and legumes in general provide a natural source of N to the cropping system (Lynch et al. 2012) compared with the cash crops of carrot and beans used under C2 and C3 rotations, respectively.

At tuber initiation, the significantly higher MBC was significantly affected by the application of amendments, but the extent was not influenced by the rotations (Rot × Amend) (Table 5). In contrast, the APA and *q*MBC were not affected by the rotations and the application of amendments. Small inter annual variability were observed for biological soil properties both prior to potato plantation for $NaHCO_3$-205 (Table 4) and at tuber initiation for APA and *q*MBC (Table 5). Even though the APA was not influenced by the rotations at tuber initiation, there were a trend of higher APA under C1 compared with C2 and C3 as observed prior to potato plantation. The APA under C1 was 15 and 18 % greater than C2 and C3, respectively. The enzyme activity under C1 rotation at tuber initiation is supported by the low POM-C/POM-N ratio (Table 5). However, this enzyme activity did not corroborate the results of SOC, SON, and C/N ratio and was not translated into significant high MBC under C1 (Table 5). Therefore, it is possible that the quality and not the quantity of the active SOM pool was the main driver of the enzyme activity observed under C1 rotation. Among the fertility treatments, the low MBC and *q*MBC observed in PMB amended soils were consistent with the associated high C/N ratio. The MBC is a sensitive parameter to changes in C input and availability of C (i.e. lignin/N ratio and C/N ratio). The addition of amendments only significantly influenced the MBC with high MBC under the soil amended with MSW compost. The range of MBC at tuber initiation (142–216 kg ha^{-1}) was lower than the range (217.9–297.4 μg C g^{-1}) reported by Nelson et al. (2009) over 2 years for four organic potato farms in Atlantic Canada. This range was comparable to that reported by Carter et al. (2003) for a long-term 3-year conventional potato rotation and by Angers et al. (1999) for conventional potato rotations in Prince Edward Island, Canada. There was also a trend of high *q*MBC under the soil amended with MSW even though the effect was not significant ($P = 0.058$). Higher MBC in MSW compared with the PMB treatment in our study can be attributed to a lower C/N ratio, and higher pH and nutrient concentrations in the MSW compared with PMB (Table 3). The *q*MBC corroborates the results obtained by Carter et al. (2009) but is lower than the range reported by Nelson et al. (2009). Generally, an increasing *q*MBC reflects a greater degree of soil biological activity associated with organic C inputs (Gregorich et al. 1994). Crecchio et al. (2001) showed that short-term MSW applications (12 and 24 Mg ha^{-1}) increased dehydrogenase and nitrate reductase activities in the soil. Crecchio et al. (2004) also found that addition of MSW resulted into significant increases in dehydrogenase (9.6 %), b-glucosidase (13.5 %), urease (15.4 %), nitrate reductase (21.4 %) and phosphatase (9.7 %) activities compared with the control treatment. Sewage sludge after an 8-year application to a cropped land also had similar effects on urease, phosphatase and glucosidase activities, the number of microorganisms, the percentage as well as the chemical composition of humic substances as observed by Sastre et al. (1996).

Soil chemical properties

Prior to potato plantation, the soil pH, P_{M3}, NO_3–N and NH_4–N were not influenced by the three potato-based 3-year rotation systems (Table 4). A trend of numerically higher NO_3–N and NH_4–N, however, was observed under C1 probably due to the occurrence of RCl persisting throughout the 2 years preceding potato plantation. This trend of higher NO_3–N and NH_4–N observed under C1 can also be explained by the higher dry matter input of second year RCl compared with OPV mixture. Some significant inter-annual variability was observed for P_{M3} and NO_3–N. Several other studies in Atlantic Canada have reported high spatial, seasonal and annual variation in soil NO_3–N (Sharifi et al. 2007, 2009). The above normal precipitation obtained in June 2010 could explain the low soil NO_3–N and NH_4–N measured at planting (Table 1). High precipitation increases soil moisture content and the high mobility of NO_3^- promotes NO_3–N leaching. The risk of NO_3–N leaching is generally higher in shallow-rooted crops that have low N recoveries, particularly when grown on coarse-textured soils and receive large inputs of N fertilizer, for example, potato and corn (St. Luce et al. 2011). Pang et al. (1998) studied nitrate leaching from soils under different N and irrigation management practices and different weather conditions and found that the factors affecting the risk of NO_3^- leaching were in the order of irrigation schedule > climatic variability > N fertilizer application rate. Through simulating NO_3^- transport under heavy rainfall and high-intensity irrigation rates in the North China Plain with the HYDRUS-1D model, Wang et al. (2014) reported that NO_3^- leaching in wet years was significantly greater than that in dry or a normal years. The small inter-annual variability observed for P_{M3} (6 % greater in 2008 than 2012) could be associated with differences in soil phosphorus due to within field variability. No significant interaction effects were found between treatments on soil chemical properties.

At tuber initiation, NO_3–N levels, but not P_{M3} and NH_4–N were significantly greater for C1 than C2 and C3, and 2008 than 2010 (Table 5). The P_{M3} was on average 320 kg ha^{-1} and was greater than the values reported by Sanderson et al. (2002) who found that 63 % of potato fields in Prince Edward Island tested over 216 kg ha^{-1} P_{M3} in 1999. The inter-annual variability observed at potato planting for P_{M3} was also observed at tuber initiation and the explanations were discussed. The lack of significant effects of fertility treatments on P_{M3} is due to similar input of P (60 kg P_2O_5) from all composts and FERT treatments. In addition, the high P_{M3} content indicates that enough P was not taken up from the soil at potato initiation to induce significant differences between CONT and the other treatments (Table 5). The high NO_3–N under C1 can be explained by the occurrence of the short lived biennial RCl persisting throughout the 2 years preceding potato plantation. Red clover and other green manure species accumulate soil mineral N. After incorporation into the soil, microbial processes will lead to mineralization of the green manure N (Askegaard and Eriksen 2008). Increased NO_3–N under C1 compared with C2 and C3 rotations can lead to NO_3- leaching and pose an environmental risk since NO_3- that is leached can eventually enter ground and surface water leading to reduced fresh water quality and eutrophication of aquatic systems (St. Luce et al. 2011). The inter-annual variability observed at potato planting for NO_3–N levels and discussed above was also observed at tuber initiation and the explanations were discussed. Soil NO_3–N measured in the spring after incorporation of different green manures in the prior autumn were in the higher end of the range (2–124 kg ha^{-1}) reported by Zebarth et al. (2003) for 228 conventional potato fields in New Brunswick, Canada. Our values are closer to average NO_3–N reported by Sharifi et al. (2009) for spring NO_3–N measurements after white clover/Pea mixture (90 kg N ha^{-1}) in Maine, USA. Huxham et al. (2005), in Britain, reported spring NO_3–N levels (to 90 cm soil depth) of 98 and 120 kg ha^{-1} following two years of green manures of hairy V and RCl, respectively. High NO_3–N values measured in 2008 in our study support the importance of green manure as source of N for potato production in this region, however it also raises the concern over fall incorporation of green manure and high potential for winter losses of N (Sharifi et al. 2009).

Agronomic implications

Green manures or cover crops are useful to improve and/or restore the selected soil quality parameters and fertility. The short lived biennial RCl is used as a green manure for its persistence in the field which last for about 2 years. However, a major obstacle for many growers using RCl in extended potato rotation systems in Nova Scotia is the lack of income generated by the land during this two-year period. Our results indicate that growing carrot or beans during the first year of the rotation followed by a mixture of OPV during the second year of the rotation yielded similar effects on soil physical properties as the conventional short lived biennial RCl.

Conclusion

The combination of annual cash crops and annual legume green manure resulted in similar effects on selected soil quality parameters compared with biennial legume green manure, with the exception of potentially mineralizable N, acid phosphatase enzyme activity, and NO_3–N. Our findings suggest similar soil physical, biological, and chemical property outcomes for an annual green manure (vetch) compared with a biennial green manure (red clover) in a three-year organic potato rotation. Replacing a biennial- with an annual-green manure allows organic potato growers to include a low demand cash crop (i.e. carrots, beans) in their rotation and has economic implications. The composted PMB and MSW maintained the chemical soil properties but, improved the physical and biological soil properties compared with the FERT treatment. We conclude that off-farm bio-waste composts can be used as soil conditioners in organic potato production. Our results demonstrated the direct and indirect (environmental services) economic potential of using annual legume green manure and off-farm composts for organic potato growers.

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