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The Benefits of Crop Rotation Including Cereals and Green Manures on Potato Yield and Nitrogen Nutrition and Soil Properties

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Abstract

Soil quality decline is a common concern in potato production systems. Including cereals and green manures (GMs) in potato rotation could improve soil productivity and sustain potato (*Solanum tuberosum* L.) yields and quality. This experiment initiated in Québec, eastern Canada, assessed the effects of two cycles of 2-yr potato rotations with cereals and GMs on soil properties and potato yield and quality, and on disease incidence from 2008 to 2011. Three cereals [corn (*Zea mays*), barley (*Hordeum vulgare*), and oat (*Avena sativa*)] seeded in spring, three summer GMs [mustard (*Sinapsis alba*), japanese millet (*Setaria italica*), and pearl millet (*Pennisetum glaucum*)], four fall GM crops [oat, mustard, wheat (*Triticum aestivum*), and rye (*Secale cereale*)], and continuous potato (*Solanum tuberosum* L.) were grown on main plots in 2008 and 2010. In following years (2009 and 2011), each main plot was split, and five N fertilizer rates (0, 50, 100, 150 and 200 kg N ha^{-1}) were applied to potato. After two rotation cycles in 2011, soils under cereals and summer and fall GMs had higher soil water-extractable organic C and N contents, nitrate levels, soil respiration, urease and dehydrogenase activities, and a larger proportion of soil macro aggregates (0.25 to 2 mm), compared with the continuous potato. Cereals and summer GMs increased marketable potato yield and specific gravity, whereas fall GMs increased tuber yield but reduced tuber quality. In addition, fall GMs favored the incidence of common scab and black scurf. Summer GMs had higher potato N uptake and N efficiency compared to cereals and fall GMs. Although fall GMs produced higher net returns than cereals and summer GMs, they may not represent a viable long term option to sustain potato production and to enhance soil quality. Results indicated that growing cereals or summer GMs in rotation with potato is an interesting alternative to improve soil properties while sustaining potato yield and quality. A fall GM with a better growth during the fall season may sustain potato yield and quality, if included in longer potato rotation, but this remains to be determined.

Keywords: Cereals in potato rotation; Summer and fall green manures; Potato yield and N efficiency; Disease incidence; Net benefit; Soil properties changes

Introduction

Potato is an important crop worldwide. In the last 50 years, yields of potato have been relatively constant in spite of the increase in chemical inputs [1]. Nitrogen inputs are often higher than potato requirements to ensure acceptable tuber yield and quality [2]. However, excess N can delay maturity and senescence of plants and decrease yields and specific gravity of the tubers [3]. Moreover, residual N is prone to be leached causing environmental issues [4] especially on sandy soils [5], which are well adapted to potato production because of their low water-holding capacity. The potential of N losses is also exacerbated by the low potato N use efficiency due to its shallow and poorly developed root system [6]. Overall, the potato crop returns low amount of organic residues to the soil and frequent potato cropping often leads to soil structural degradation due to the depletion of soil organic matter [1,7].

Management practices that add organic matter such as crop rotations and GMs have proved to be efficient in enhancing the sustainability of intensive potato production [8], with positive effects on potato yields and soil organic matter content, structure, microbial biomass, and fertility [1,7,8]. Once incorporated into the soil, green manure crops may contribute to following potato nutrition because much of the nutrients retained by GMs become available through decomposition and mineralization processes [9]. According to Weinert et al. [10], GMS can provide to the following crop between 20% and 55% of their N fertilizer requirements [10]. However, the ability of GMs to release N depends on their chemical composition, including the C: N ratio, and lignin and polyphenol contents, and on environmental conditions such as soil moisture and temperature [11,12]. Furthermore, the N supply from GMS varies depending on its yield and N content [3,12]. To maximize the N use efficiency while minimizing the N loss, the amount and the timing of N release from GMS must be synchronized with the subsequent potato N needs for maximum tuber yields [13].

Compared to non-legumes, legume crops are more important sources of N for subsequent potato crop since they can biologically fix significant amounts of N_2 [13]. In some potato-based crop rotations, different legume crops have been found to supplying 25 to 260 kg N ha^{-1}[14]. However, legumes are not popular green manure crops in potato based rotations because farmers are concerned with the potential increase in diseases such as common scab [7,14] representing the fourth most economically important disease for potato production in North America [15]. Moreover, establishment costs of legume crops can also be 10 times higher than grasses species [14]. Non-legume green manure crops could have high potential as alternative rotation crops for potato and provide significant quantity of N to subsequent crops by capturing soil nutrients. When grown in the fall after harvest of the main cash crop, GMS can be used to retain residual fertilizer N and other

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nutrients that could otherwise be leached out of the cropping systems. Typical non-legume species used as green manure include cereals such as rye, millet, wheat, oat, and buckwheat (*Fagopyrum esculentum*) and *Brassicaceae* such as mustard, canola, and radishes [10,12,13]. Crop rotations including GMs may also enhance potato yields and quality by breaking the cycle of weeds, pests, and diseases, although their action mechanisms are varied and often unknown [16]. *Brassica* species are often considered the most effective to suppress soil-borne diseases, likely because of their high contents in glucosinolates which breakdown in toxic compounds such as isothiocyanates [14,17]. Incorporation of GMs may also stimulate other microorganisms that help biological control of potato diseases through competition [16,18].

Potato has a high value by unit surface cultivated and, thus, potato producers prefer short rotation cycles [7]. Despite its potential multiple benefits on soil quality and potato productivity, growing GMs during the regular cropping season usually results in a loss of income [14]. On the other hand, GMs planted in the fall must have rapid growth, great biomass production and nutrient scavenging ability. In eastern regions of Canada, continuous potato cultivation has been progressively replaced by crop rotations with corn and spring cereals such as oat, barley, and rye [19] that contribute to add significant quantities of organic matter to the soil. However, choosing the best crop rotation for potato is still challenging. Potato producers prefer to include cash crops in potato rotation, or to grow fall GMs after potato harvest. The impact on soil properties and potato yield and quality may depend on the crop specie included in rotation. This 4 year study (two successive cycles of a 2 y potato crop rotations) aimed to compare the different potato rotations with such as cereals, including oat, barley, and corn, and with GMs seeded either in summer (mustard, Japanese millet and pearl millet) or in the fall (oat, mustard, wheat and rye) on potato yield, net income, N nutrition, disease incidence and on soil properties changes.

Materials and Methods

Site description and experimental design

A 4 yr study was conducted from 2008 to 2011 at the research station of the Institut de Recherche et Développement en Agroenvironnement located in Deschambault, Québec, eastern Canada (46°41'27"N; 71°58' 18" O). The soil was a fine sandy loam of the Batiscan series (sandy over clayey, mixed, non-acid, frigid, Typic Humaquept) with on Average 490 g kg^{-1} sand, 300 g kg^{-1} silt and 210 g kg^{-1} clay. The initial soil pH (water) was 6.3, and the soil total C and N contents were 40.0 g kg^{-1} C and 1.9 g kg^{-1} N. The soil available P and K contents were 81.0 and 46.0 mg kg^{-1}, respectively. Cereal and green manure crops were grown in 2008 and 2010, while potato was grown in 2009 and 2011. During the four cropping seasons (May-September), mean air temperatures were 14.2, 13.2, 15.6 and 15.5°C in 2008, 2009, 2010 and 2011, respectively and total precipitation was 749.6, 681.6, 517.2, and 468.3 mm, respectively (Table 1). In the four years of the experiment, potato crop was not irrigated.

Temperature(°C)				
Months	**2008**	**2009**	**2010**	**2011**
May	9.4	9.4	12.3	14.8
June	16.4	13.6	15.8	19.3
July	18.2	17.3	20.4	21.2
August	17.3	15.2	18.2	17.9
September	12.8	12.3	13.6	14.7
October	10.9	11.6	12.5	10.8
Rainfall (mm)				
May	59.4	97.5	68.9	92.3
June	180.9	76.2	74.6	52.3
July	167.7	151.9	92.8	44.2
August	106.1	140.5	77.7	91.8
September	103.4	88.8	90.8	80.8
October	132.3	126.7	112.4	106.2

Table 1: Temperature and rainfall at Deschambault Research Station (2008-2011).

This research was conducted to determine the effect of various previous crops and GMs on potato yield, disease incidence and soil properties in two cycles of a two-year potato rotation. Previous cash crops (cereals), summer GMs, fall GMs, and continuous potato were compared. In the years following cereals and GMS cultivation as main treatments, the plots were split to accommodate 5 fertilizer N rates. The experiment was conducted over 4 years using a randomized complete block design in years with the crop rotations, and a split-plot design in years when N rates were tested.

The experiment was laid out in a complete randomized block design with three replications. Each block was divided in 11 experimental units of 30 by 6 m. Treatments established in 2008 and 2010 on the same field consisted of a control with continuous potato (*Solanum tuberosum* L.), cereal-potato rotations [corn (*Zea mays*), barley (*Hordeum vulgare*) and oat (*Avena sativa*)], summer GMs [mustard (*Sinapsis alba*), japanese millet (*Setaria italica*) and pearl millet (*Pennisetum glaucum*)], and potatoes followed by fall GMs [oat, mustard, wheat (*Triticum aestivum*) and rye (*Secale cereale*)].

The periods of seeding and harvest of the different crops are summarized in Table 2. Cereals and summer GMs were seeded in May 2008 and 2010, whereas potato was planted at the same period in plots for the fall GMS and control treatments. Fall GMs were established after potato harvest at the end of August in 2008 and in the mid-September in 2010 due to heavy rainfall that delayed potato harvest. To avoid the use of a same cultivar in the four years of the experiment, potato (cv. Norland) which is a common cultivar in eastern Canada and is tolerant to common scab, was planted at 43000 pl ha^{-1} in the years of crop rotation establishment (2008 and 2010). Corn hybrid used in the experiments were Dekalb-343-2550 corn heat units (CHU) at 80,000 plants ha^{-1}, and oat (cv Rigodon) and barley (cv. Myriam) were seeded at 120 and 150 kg ha^{-1}, respectively. Mustard, pearl millet and Japanese millet as summer GMs were seeded at 21,40 and 30 kg ha^{-1}, respectively. Fall GMs (oat, mustard, wheat, and rye) were seeded at 120, 21,160 and 120 kg ha^{-1}, respectively. Potato and corn received N fertilizer at a rate of 170 kg N ha^{-1} as calcium ammonium nitrate (27%). Phosphorus and K were applied at a rate of 50 kg P_2O_5 ha^{-1} as super-phosphate and K at a rate of 150 kg K_2O ha^{-1} as KCl. Nitrogen fertilizers for oat, barley and summer GMs were applied at a rate of 50 kg N ha^{-1}, 50 kg P_2O_5, and 150 kg K_2O ha^{-1} with the same fertilizer types as above. Fall GMs were seeded after potato harvest and were not fertilized as they may use residual fertilizer N that could otherwise be leached out of the field.

Cereal grain yields were determined by harvesting in mid-August a surface of 1.5 by 6 m in the center of each plot with a combine. Corn was harvested in late October in the two central rows from each plot. After harvest, cereal straws and corn stalks were collected, weighed, and organic residues left on the soil. Summer GMs were harvested in August at the flowering stage. Total aboveground biomass was determined and the biomass was returned to the soil and incorporated by disc harrowing to a depth of 10 cm. In both years (2008 and 2010), the pearl millet biomass was chopped in August and left on the soil, and the plants were left to regrow in the fall. Potato in the check plots and in soils with fall

Crops	Seeding Rates	Seeding Periods	Harvest/growth termination Times 2008
Potato	43000 pl ha^{-1}	21 May	25-Aug
Oat	120 kg ha^{-1}	25 May	17-Sep
Barley	150 kg ha^{-1}	26-May	17-Sep
Corn	80000 grains	30-May	30-Oct
Mustard	21 Kg ha^{-1}	25-May	14-Aug
Japanese Millet	40 kg ha^{-1}	25-May	14-Aug
Pearl Millet	30 kg ha^{-1}	26-May	21-Aug
Potato/	43000 pl ha^{-1}	21-May	25-Aug
Oat	120 kg ha^{-1}	27-Aug	04-Nov
Potato/	43000 pl ha^{-1}	21-May	25-Aug
Mustard	21 Kg ha^{-1}	27-Aug	04-Nov
Potato/	43000 pl ha^{-1}	21-May	25-Aug
Wheat	165 kg ha^{-1}	27-Aug	04-Nov
Potato/	43000 pl ha^{-1}	21-May	25-Aug
Rye	120 kg ha^{-1}	27-May	04-Aug
Crops	**Seeding Rates**	**Seeding Periods**	**Harvest/growth termination Times 2010**
Potato	43000 pl ha^{-1}	21 May	25-Aug
Oat	120 kg ha^{-1}	25 May	17-Sep
Barley	150 kg ha^{-1}	26-May	17-Sep
Corn	80000 grains	30-May	30-Oct
Mustard	21 Kg ha^{-1}	25-May	14-Aug
Japanese Millet	40 kg ha^{-1}	25-May	14-Aug
Pearl Millet	30 kg ha^{-1}	26-May	21-Aug
Potato/	43000 pl ha^{-1}	21-May	25-Aug
Oat	120 kg ha^{-1}	27-Aug	04-Nov
Potato/	43000 pl ha^{-1}	21-May	25-Aug
Mustard	21 Kg ha^{-1}	27-Aug	04-Nov
Potato/	43000 pl ha^{-1}	21-May	25-Aug
Wheat	165 kg ha^{-1}	27-Aug	04-Nov
Potato/	43000 pl ha^{-1}	21-May	25-Aug
Rye	120 kg ha^{-1}	27-May	04-Aug

Table 2: Crops in potato rotation in 2008 and 2010, and seeding and harvest periods. Potato was seeded as subsequent crop in the same fields in 2009 and 2011.

GMs was harvested at the end of August in 2008 and in mid-September in 2010 on 6 m row sections of the two middle rows of each plot to measure tuber yields. Pearl millet and fall GMs were hand harvested in late November on three 6 m, and the total aboveground biomass was determined and returned to the soil. Thereafter, all plots of the experiment were tilled to a depth of 15 cm. At each crop harvest, organic residues and vegetative biomass were sampled to determine dry matter and N contents.

In 2009 and 2011, the main plots with the rotations crops were divided in five subplots to which five N fertilizer rates for potato were randomly assigned: 0, 50, 100, 150, and 200 kg N ha^{-1}. The experiment design was a split-plot with crop rotations seeded in the same fields in 2008 and 2010 as main plots, and N fertilizer rates as subplots in 2009 and 2011. Each subplot was 6 m long and 6 m wide, and consisted of 6 rows with 0.90-m row spacing. Nitrogen fertilizer was applied as calcium ammonium nitrate (27%) and was split-applied in two fractions: the first 50 kg N ha^{-1} as a starter fertilizer and the remaining N fertilizer was added at the tuber initiation development stage. Phosphorus and K fertilizers were applied at seeding at rates of 50 kg P_2O_5 and 150 kg K_2O ha^{-1} as triple superphosphate and KCl, respectively. Potato (cv Snowden) is the most popular cultivar in potato chips industry, and is susceptible to common scab. To avoid the disease incidence, potato (cv. Norland) which is tolerant to common scab was planted in 2008 and 2010 in the treatments with fall GMs and with continuous potato as control. In spring 2009 and 2011, potato (cv. Snowden) was planted at 43000 plants ha^{-1} Titan treatments were applied against potato beetles, Quadris against black scurf (R*hizoctonia solani* Kühn), Allegro 500 EF against potato fungal diseases (*Phytophtora infestans* and *Alternaria solani*), and pentachloronitrobenzene (PCNB) for common scab (*Streptomyces scabies*)

Soil and plant sampling and analysis

Soil samples were collected in spring 2008 at 20 cm depth in the experimental field before initiation of the experiment. Ten soil cores were taken randomly with a 2 cm diam. stainless auger (Oakfield model B, Oakfield Apparatus Co. Oakfield, WI), and bulked to make one composite soil sample. Twenty soil samples were then obtained, air-dried and sieved to pass a 2-mm sieve to determine soil pH, soil texture, and available P and K contents. Sub-samples were ground to pass a 0.25-mm sieve for total C and N analyses. Soil pH was measured in 1:1 soil/water solution. Extractable soil P and K contents were determined in a Mehlich III solution [20] and measured on inductively coupled plasma optical emission spectrometer (Perkin Elmer 4300 DV, Boston, MA). The soil C and N contents of the whole soil were determined by dry combustion using an automated analyzer (Leco C-N 1000, LECO, St. Joseph, MI). Particle size analysis (texture) was performed using the pipette method after the destruction of organic matter with H_2O_2 and dispersion with sodium hexametaphosphate [21].

In 2011, soil samples were collected before potato seeding and fertilizer application, in main plots with previous rotational crops. Ten soil cores were taken from each plot at 0-30 cm depth and pooled to make one composite soil sample, air-dried and sieved to pass a 2 mm sieve for pre-plant soil nitrate test (PPNT). A sub-sample was ground to pass a 0.25 mm sieve for C and N analyses. At the potato tuber initiation growth stage, soil samples were collected only in the 0 kg N ha^{-1} N rate treatment of each previous crop at 0-30 cm depth to determine changes in soil physical and biological properties and soil pre-sidedress (PSNT) contents following two cycles of 2 yr potato rotations with cereals and green manure crops. Ten soil cores were taken between rows in each plot, pooled to make one composite soil sample, sieved to pass a 2 mm sieve and then stored at 4°C until analysis. A portion of the moist soil samples was used to assess various microbial activities (respiration, urease, alkaline phosphatase, and dehydrogenase).

Soil respiration was measured according to the soil incubation method as described by Anderson [22]. Briefly, wet soil samples (100 g) were incubated in triplicate in 1-L Erlenmeyer flasks at 30° for 20 days. The quantity of CO_2 released was trapped using 10 mL of 1.0 M NaOH and determined by titration after adding 1.5 M $BaCl_2$ in excess. Dehydrogenase activity was determined by colorimetric measurement of triphenyltetrazolium formazan (TPF) produced by the reduction of 2,3,5-triphenyltetrazolium chloride (TTC) according to the method of Casida et al. [23]. Alkaline phosphatase activity was determined by colorimetric measurement of the p-nitrophenol released when 1 g of field-moist sample was incubated with 4 mL of buffered (pH 11) sodium p-nitrophenyl phosphate solution, 0.2 mL of toluene and 1 mL of p-nitrophenol phosphatase at 37°C for 1 h [24]. Urease activity was determined on field-moist soil samples (2.5 g) incubated at 37°C for 2 h and the amount of NH^+ produced was determined by N spectrophotometry at 636 mM using indophenol blue [24]. The concentrations of soil nitrate before seeding (PPNT) and at post-seeding (PSNT) were determined with 2M KCl [25]. The soil C and N contents of the whole soil were determined by dry combustion using an automated analyzer (Leco C-N 1000, LECO, St. Joseph, MI). Water-extractable organic C (WEOC) and N (WEON) were extracted with cold water on air-dried soil ground to 0.25 mm following the method of Curtin et al. [26]. The concentration of WEOC was determined by wet combustion (Model TOC, 5000, Shimadzu Corp., Kyoto, Japan) and the concentration of WEON with an automated colorimeter (Model AA II, Technicon Instruments, Tarrytowmn, NY).

Three intact soil blocks of about 600 g (0-30 cm depth) were taken between rows in the 0 kg N ha^{-1} N rate treatment of each previous crop with a spade, to assess the soil water-stable aggregates. Soil blocks were sieved at 5 mm in the field and kept at 4°C until analysis. Water-stable soil macroaggregates were determined by the wet-sieving method. Forty grams were put on the top of a series of sieves (5,2,1, and 0.25 mm), which were immersed in water and shaken for 10 min. The soil fractions recovered on each sieve were dried at 65°C for 24 h, corrected for sand content and expressed as a percentage of total dry soil [27]. Aggregate mean weight diameter (MWD) was calculated according to Haynes and Beare [28].

Potato yield, quality and N efficiency determination

In 2009 and 2011, potato was harvested on 10 m row sections of the two middle rows of each plot to measure tuber yields. The tubers were weighed and tuber size categories and marketable (47-114 mm diam.) yield determined. A representative 4 kg sub-sample of tubers was taken from each plot to determine tuber dry matter, specific gravity, N concentration, and presence of diseases. Ten representative tubers from each plot were quartered along the long axis, and one quarter from each tuber was sliced into strips of 1 cm × 1 cm, weighed, oven dried at 55°C, and re-weighed to determine dry matter content. The tuber samples were ground to pass a 0.15 mm sieve for total N determination. Potato specific gravity was determined from three samples per plot by using the "weight in air/weight in water" method. Randomly selected tubers from each plot were rinsed with water and rated for common scab (*Streptomyces scabiei*) and black scurf (*Rhizoctonia solani* Kühn) occurrence. Disease severity was determined using a rating scale of zero to six based on the percentage of tuber surface covered with scab or black scurf lesions, i.e., 0, 0%; 1, 1%-5%; 2, 6%-15%; 3, 16%-25%; 4, 26%-35%; 5,36%-60% and 6.61%-100% [29]. The C and N concentration of potato tubers and green manures were determined by dry combustion (Leco C-N 1000, LECO, St. Joseph, MI, USA).

Potato nitrogen fertilizer efficiency (NFE) was determined as described by Wortman et al. [30]: NFE (kg tuber kg^{-1} N applied)=(Tuber yield from N fertilized plot-Tuber yield from unfertilized plot)/N applied × 100; Nitrogen recovery efficiency (NRE) was calculated as per Zvomuya et al. [31]: $NRE=(N_{treat}-N_{control})/N_{applied} \times 100$, where N_{treat} represents the amount of nitrogen stored in the tubers of a given fertilizer treatment, $N_{control}$ is the amount of N stored in the tubers of the control plot.

Economic analysis

Net returns were determined annually for each crop rotation system as the difference between gross margins and total variable costs, both of which were determined using the local market prices published in economic references [32]. Variable costs included inputs costs (seeds, fertilizers, limestone, pesticides, fuel, oil, and lubricants), field operation costs (tillage, harrowing, sowing, pulverizing, harvest), sale costs related to drying grain (propane gas and electricity, dryer maintenance) and crop insurance. Gross margins were generated by sale of grains, straw, and income from the local crop insurance program (Programme d'assurance de stabilisation des revenus agricoles, ASRA, Financière Agricole du Québec). Gross margins were computed per hectare by multiplying the yield of each crop by its local market price.

Statistical methods

Data were analyzed separately for each year of the experiment (2009 and 2011) and analysis of variance performed using PROC MIXED of SAS [33] treating potato preceding crops and N fertilizer rates as fixed effects and block as random. Type III F tests were performed for the fixed factors and a priori contrasts were used to compare treatment means when the preceding crop effect was found significant at the 0.05 probability level. Different crop groups were compared: 1. continuous potato, 2. cereal crops, 3. summer GMS, and 4. fall GMs. When the N rate effect was significant ($P<0.05$), orthogonal polynomial contrasts were performed to assess if effect of the N fertilizer effect was linear or quadratic. For soil properties changes measured in 2011, a one-way ANOVA was used to compare the effect of the preceding crops on the soil parameters. Mixed procedure of SAS was used to conduct statistical analysis treating the preceding crops as fixed factors and blocks as random. Crop groups as above were compared using contrasts when the preceding crop effect was significant at 0.05 probability level. A one-way ANOVA was also used to compare physical and chemical characteristic of rotational crops in 2008 and 2010. A priori contrasts were also used to compare the different preceding crops.

Results and Discussion

Green manure biomass and nitrogen accumulation

Quantities of biomass, carbon and nitrogen incorporated in soil from different previous crops: For summer GMs, the amounts of aboveground biomass varied from 4.1 to 8.4 Mg dry matter ha^{-1} in 2008 and from 5.3 to 8.8 Mg ha^{-1} in 2010, and were the lowest for yellow mustard (Tables 3 and 4). The amounts of C returned to the soil following the incorporation of summer GMs varied from 1558 to 3336 kg C ha^{-1} in 2008 and from 2067 to 3520 kg C ha^{-1} in 2010. The amounts of N returned to the soil varied between 78 and 95 kg N ha^{-1} in 2008 and between 124 and 138 kg N ha^{-1} in 2010, and were highest for summer GMs over two years. Despite its low biomass yield, yellow mustard supplied similar amounts of N as the other summer GMs, likely due to its greater N scavenging ability as compared with Japanese and pearl millet. In both years, fall GMs produced lower biomass yields (1.2-2.0 Mg ha^{-1}) and supplied less C (444-840 kg C ha^{-1}) and N (47-77 kg N ha^{-1}) to the soil than summer GMs (Tables 3 and 4). This could be explained in part by the shorter period of time elapsed between planting and harvesting of fall GMs, as compared with summer GMs. Average air temperatures are likely lower in the fall than in the summer, and the days are shorter with less daily global radiation. Fall GMs aboveground biomass, C and N contents returned to the soil were lower in 2010 than in 2008 because heavy rainfall in August and September 2010 altered crop growth. Corn stalk yields were 4.3 and 3.3 Mg ha^{-1} in 2008 and

Crops	Dry matter Mg ha^{-1}	C kg ha^{-1}	N kg ha^{-1}	C g kg^{-1}	N g kg^{-1}	C/N
Summer GMs£						
Pearl millet	8.3	3336	83	402	12	34
Yellow mustard	4.1	1558	95	380	24	16
Japanese millet	7.2	2786	78	387	12	32
Fall GMs						
Oat	2	840	53	420	28	15
Wheat	1.9	798	52	420	27	16
Mustard	2	744	77	372	39	10
Rye	2.1	873	59	416	30	14
Cereals						
Corn	4.3	1892	21	440	4.9	90
Barley	2.9	1282	16	442	5.6	79
Oat	2.6	1139	17	438	6.4	68
Analysis of Variance (P value)						
Crop effect	<0.0001	<0.0001	<0.0001	ns	<0.0001	<0.0001
Contrasts						
1,2,3 vs 4,5,6,7	<0.0001	<0.0001	<0.0001	ns	<0.0001	<0.0001
1,2, 3 vs vs 8,9,10	<0.0001	<0.0001	<0.0001	ns	<0.0001	<0.0001
4,5,6.,7 vs 8,9,10	<0.0001	<0.0001	<0.0001	ns	<0.0001	<0.0001

£GMs: green manures; ns, not significant.

Table 3: Dry matter, carbon and nitrogen contents, and C/N of different crops in 2008.

2010, respectively and barley and oat straw yields were 2.7 and 2.3 Mg ha^{-1}, respectively. The N concentrations of corn stalk and cereal straws were low (4.9 to 7.5 g kg^{-1}) and their N input in the soil varied from 15 to 21 kg ha^{-1} (Tables 3 and 4). In 2008 and 2010, the C returned to the soil by cereal residues varied from 913 to 1892 kg C ha^{-1}.

The C/N ratio for summer and fall GMs manures varied from 10 to 34, indicating that these organic residues may have a high mineralization rate, except for Japanese millet with a C/N of 34 which could induce a slight N immobilization. Organic mineralization rate is mainly controlled by their biochemical composition, such as C/N ratio and polyphenol, lignin, and nitrogen contents [34,35]. Fall GMs had lower C/N ratios than summer GMs (Tables 3 and 4), which suggests that they may decompose and release N more rapidly. The C/N ratio was 88 for corn stalk and 63 and 74 for oat and barley, showing that these organic residues with high C/N ratios may decompose slowly in soil, and their influence on soil microbial activity and aggregation is low [36]. The author observed that potato tuber yield declined following oat cover crop with a high C/N ratio due to its low rate of N mineralization. Results showed that the biochemical composition of the studied crops was different, therefore, their effects on soil N availability and on soil properties changes may differ.

Effect of cereals and green manures on soil properties soil total and dissolved carbon and nitrogen contents: Total soil C and N contents varied from 21 to 23 g C kg^{-1} and from 1.6 to 1.8 g N kg^{-1} (Table 5). Soil total C and N contents were not significantly increased after two cycles of crop rotations with cereals (barley, oat and corn) and summer and fall GMs. This finding is in accordance with other studies reporting that changes in soil organic matter content are gradual and not detectable in short-term rotations [37]. Contradictory results, however, were obtained by other investigators [12,38]. For instance, N'Dayegamiye and Tran [12] found that cultivating GMs, such as millet, mustard, and canola for one year significantly increased C and N contents of a silt loam soil. These results may be related to different conditions under which the experiments were conducted, including the use of different GMs species, different amounts and quality of green manure biomass returned to the soil, climatic conditions, and different soil types. It is well documented that clay soils retain more organic matter than sandy soils [39], because organic matter associated with clay minerals benefit more physical and chemical protection against decomposition than that associated with sand [35,40]. Potato is mostly cultivated on sandy soils and the decline of soil organic matter is of much concern. The low soil organic matter and N accumulation observed in the present study indicates that the total quantities of organic residues (3 to 16 Mg ha^{-1}) and C (1000 to 3800 kg C ha^{-1}) incorporated in soils in 2008 and 2010 were not sufficient to induce an increase in soil organic matter. N'Dayegamiye [35] showed that three paper-mill sludges applications at 40 to 60 Mg ha^{-1} yr^{-1} significantly increased the soil C content. Moreover, GMs as used in the study also contain readily mineralizable organic materials as suggested by their low C/N ratios (Tables 3 and 4), and that they were likely mineralized more rapidly in the sandy soil of the present study than in the silt loam studied by N'Dayegamiye et Tran [12] and N'Dayegamiye [35]. Soil water extractable C and N (WEOC, and WEON) concentrations varied from 110 to 140 mg C kg^{-1}, and from 15 to 24 mg N kg^{-1}, respectively (Table 5). By contrast to soil total C and N contents, soil WEOC and WEON concentrations were both significantly ($p<0.01$) increased by the preceding crops in comparison with continuous potato. While WEOC did not vary significantly among the preceding crops, contrast analysis showed that WEON concentrations were larger in soils previously cropped to cereals and summer GMs than in those previously cropped to fall GMs or under continuous potato (Table 5). On average, soil WEOC contents were 17% higher in soils under the cereal-potato rotations and following summer and fall GMs than in

Crops	Dry matter Mg ha^{-1}	C kg ha^{-1}	N kg ha^{-1}	C g kg^{-1}	N g kg^{-1}	C/N
Summer GMs£						
Pearl millet	8.8	3520	133	400	15	26
Yellow mustard	5.3	2067	138	390	25	16
Japanese millet	8.3	3237	131	390	15	26
Fall GMs						
Oat	1.2	504	48	420	40	11
Wheat	1.2	504	53	420	45	9
Mustard	1.2	444	47	370	36	10
Rye	1.3	559	53	430	40	10
Cereals						
Corn	3.3	1468	17	445	5.1	87
Barley	2.5	1102	15	441	6.2	70
Oat	2.1	913	16	435	7.5	58
Analysis of Variance (P value)						
Crop effect	<0.0001	<0.0001	<0.0001	ns	<0.0001	<0.0001
Contrasts						
1,2,3 vs 4,5,6,7	<0.0001	<0.0001	<0.0001	ns	<0.0001	<0.0001
1,2, 3 vs 8,9,10	<0.0001	<0.0001	<0.0001	ns	<0.0001	<0.0001
4,5,6.,7 vs 8,9,10	<0.0001	<0.0001	<0.0001	ns	<0.0001	<0.0001

Table 4: Dry matter, carbon and nitrogen contents, and C/N of different crops in 2010.

those under continuous potato. These findings are in agreement with those reported by Asmar et al. [41] where the addition of fresh organic material to soil increased the amount of water-soluble organic matter.

Proceeding Crops	C g kg^{-1}	N g kg^{-1}	WEOC mg kg^{-1}	WEON mg kg^{-1}
Continuous potato	21	1.6	110	15
Barley	23	1.7	140	22
Corn	23	1.8	130	24
Oat	22	1.8	130	20
Mustard	23	1.8	130	21
Japanese Millet	21	1.8	120	16
Pearl Millet	23	1.9	120	28
Potato/mustard	23	1.8	140	17
Potato/wheat	22	1.8	140	17
Potato/Rye	23	1.9	120	18
Potato/Oat	23	1.8	120	21
Analysis of variance and contrasts (P value)				
Effect of the preceding crops	ns	ns	0.0038	0.0019
Summer GMs£ vs. fall GMs	ns	ns	ns	0.0453
Summer GMs vs. cereals	ns	ns	ns	ns
Fall GMs vs. cereals	ns	ns	ns	0.0289
Green manures + cereals vs. continuous potato	ns	ns	0.0523	0.0472

¥ 2, 3 and 4: cereal-crop rotations; 5, 6 and 7: summer GMs; 8, 9, 10 and 11: fall GMs cropped after potato harvest.

£ GMs: green manures; ns, not significant.

€ Soil sampling was done in 2011 in plots that received no N fertilizer (0 kg N ha)$^{-1}$.

Table 5: Effects of different preceding crops on soil total carbon and nitrogen, and water-extractable organic carbon (WEOC) and nitrogen (WEON) concentrations in 2011€.

These results also corroborate other studies showing that WEOC was a better indicator than total C to assess short-term changes in soil organic matter quality [42,43]. Although it accounts for a small proportion of soil organic matter, WEOC is considered the most bioavailable fraction [44] and is considered as a substrate for soil microbes [45]. In other studies, WEOC was found to be strongly correlated with macroaggregate stability, and it was suggested that it is involved in aggregates formation [46,47]. Thus, one might expect that cereal straw and corn stalks in the cereal-potato rotations and GMs which have increased water-soluble C might promote soil microbial activities and soil aggregation in the studied soil.

Soil microbial activities

Soil respiration, urease and dehydrogenase activities were higher in soils previously cropped to cereals and GMs compared with those under continuous potato (Table 6). Soil alkaline phosphatase activity was not significantly increased by the preceding crops. Contrast analysis showed that soil respiration and urease activity were higher in soils previously cropped to cereals than with GMs, and did not differ between summer and fall GMs treatments (Table 6). In comparison with continuous potato, soil respiration and urease activity were on average 43 and 53% greater in soils previously cropped with cereals, and 16 and 22% in those with GMs. Cereal straws and corn stalks were left on the soil and the C quantities applied to the soil were half of those added with summer GMs. The larger increase in microbial activities found in soils previously cropped to cereals suggests that more organic matter was still available for soil microorganisms likely because barley, oat and corn organic residues were more recalcitrant to microbial degradation than residues from the GMs and might thus last longer.

Our findings agree with others studies supporting that soil respiration, microbial biomass, and soil enzyme activities respond more quickly to changes in crop management than soil total C [35,48]. Increased soil respiration generally reflects an increase in soil

Proceeding Crops	PPNT mg NO^{-3}	PSNT N kg^{-}	Soil Respiration mg CO_2	Alkaline Phosphatase µg PNP g^{-1}	Urease µg N-NH4 g^{-1}	Dehydrogenase µg TPF^{-1}
Continuous potato	2	6	326	136	29	22
Barley	3	9	434	151	43	27
Corn	2.9	11	467	175	47	48
Oat	2.6	9.7	494	156	43	44
Mustard	2.8	12.6	387	143	36	32
Japanese Millet	2.3	10.3	378	131	34	39
Pearl Millet	3.6	11.7	434	162	40	49
Potato/mustard	2.9	6.8	374	133	32	24
Potato/wheat	2.5	6.7	369	139	37	41
Potato/Rye	2.9	8.3	361	153	33	42
Potato/Oat	3.4	11	354	135	35	28
Analysis of variance and contrasts (*P* value)						
Effect of the preceding crops	0.0479	0.0335	0.0313	ns	0.0452	0.0497
Summer GMs£ vs. fall GMs	ns	0.0492	ns	ns	ns	ns
Summer GMs vs. cereals	ns	ns	0.0041	ns	0.0067	ns
Fall GMs vs. cereals	ns	0.0518	<0.0001	ns	<0.0001	ns
Green manures+cereals vs. continuous potato	0.004	0.0417	0.0051	ns	0.0458	0.0384

¥2, 3 and 4: cereal-crop rotations; 5, 6 and 7: summer GMs; 8, 9, 10 and 11: fall GMs cropped after potato harvest.

£ GMs: green manures; ns, not significant.

€ Soil sampling was done in 2011 in plots that received no N fertilizer (0 kg N ha)$^{-1}$

Table 6: Effects of different preceding crops on pre-plant soil nitrate (PPNT), pre-sidedress soil nitrate (PSNT), soil respiration, and enzyme activities in 2011€.

microbial biomass [49] and, thereby, the greater respiration in soils previously cropped to cereals and GMs indicates that these preceding crops stimulated soil microbial growth and activity by supplying labile organic matter, as shown by soil WEOC (Table 5). The overall increases in soil respiration and enzyme activities should enhance the decomposition of soil organic matter and incorporated plant residues, thereby promoting soil aggregation and nutrient availability to the following potato crop [43].

Soil macroaggregates and mean weight diameter of aggregates

The proportion of soil macroaggregates (>0.25 mm diam.) varied between 31% and 62% while MWD varied from 0.78 and 1.41 mm (Table 7). Soil macroaggregates >0.25 mm represented more than 83% in silt loam which received paper mill sludge application [35] and 70% in clay loam soils with dairy cattle manure application [50]. In the present study, the preceding crops increased the proportions of soil macroaggregates 0.25-1 mm and 1-2 mm by 48% and 23%, respectively, compared with continuous potato (Table 7). This finding is consistent with other studies where the use of GMs in potato crop rotations improved water-stable aggregates [38,51]. Contrast analysis showed that the proportion of soil macroaggregates (>0.25 mm diam.) was not significantly different between the crop systems with cereals and GMs. Results showed that the preceding crops did not increase the proportion of soil macroaggregates>2 mm and MWD in studied sandy loam, contrary to N'Dayegamiye [35] who found that organic residues rapidly increased soil macroaggregates>2 mm and MWD in a silt loam. This difference may be attributed to the different soil types between studies. For example, MacRae and Mehuys [37] reported that crop rotations improved soil aggregation and bulk density of a clay soil, but had no effect on a sandy loam. N'Dayegamiye [35] found that increases of soil C contents, water-stable aggregates and MWD following application of mixed paper mill sludge and dairy cattle manure were lower in sandy loam than in clay loam soils.

Proceeding Crops	>5 mm	5-2 mm	2-1 mm	1-0,25 mm	MWD
Continuous potato	8	18.8	10.1	10.4	1.3
Barley	6.9	13.8	10.9	12.8	1.3
Corn	5.6	18.7	16.1	17	1.4
Oat	2.7	19.4	11.5	17.6	1
Mustard	3.5	15.2	11.9	20.4	1
Japanese Millet	6.2	20.5	12.4	14.3	1.3
Pearl Millet	8.7	21.6	16	15.8	1.6
Potato/mustard	2.4	10	7.8	10.9	0.8
Potato/wheat	9.6	17.5	14.8	17.6	1.7
Potato/Rye	7.8	12.6	11	10.9	1.3
Potato/Oat	3.2	15.3	12.2	17.7	0.91
Analysis of variance and contrasts (*P* value)					
Effect of the preceding crops	ns	ns	0.0471	0.0523	ns
Summer GMs£ vs. fall GMs	ns	ns	ns	ns	ns
Summer GMs vs. cereals	ns	ns	ns	ns	ns
Fall GMs vs. cereals	ns	ns	ns	ns	ns
Green manures + cereals vs. continuous potato	ns	ns	0.0452	0.0322	ns

¥ 2, 3 and 4: cereal-crop rotations; 5, 6 and 7: summer GMs; 8, 9, 10 and 11: fall GMs cropped after potato harvest.

£ GMs: green manures; ns, not significant.

€ Soil sampling was done in 2011 in plots that received no N fertilizer (0 kg N ha)$^{-1}$.

Table 7: Effects of different preceding crops on soil water-stable macroaggregate size distribution and mean weigh diameter (MWD) in 2011€.

Soil pre-plant test and pre-sidedressed nitrate test

Soil nitrate concentrations were measured on a 0-30 cm soil layer. Pre-Plant soil nitrate (PPNT) before potato seeding in 2011 varied between 2.0 and 3.4 mg kg^{-1} and Pre-Sidedress soil nitrate (PSNT) at mid-season varied between 6.0 and 12.6 mg kg^{-1} (Table 8) and were both significantly (P<0.05) increased following cereals and GMs in comparison with continuous potato. Soils previously cropped to cereals and GMs had PPNT values 47% higher than under continuous potato. Soil nitrate contents at mid-season (PSNT) were at least threefold higher than PPNT, indicating that mineralization rate of soil organic N and incorporated crop residues increased as the potato growing season progressed. As for PPNT, the lowest PSNT values were recorded in soils under continuous potato. In comparison with continuous potato, PSNT values were 36 to 78% greater in soils previously cropped to cereals and summer GMs, respectively. Contrast analysis showed that soil PSNT contents were higher following summer GMs and cereals than following fall GMs. The highest PSNT content in soils previously cropped to summer GMs is attributed to their high N input (Tables 3 and 4). The increase in soil nitrate following cereals was not expected as their residues generally add small quantities of N to soil, compared with summer and fall GMs and may induce soil N immobilization due to their high C/N ratios (Tables 3 and 4). By improving soil aggregation, the cereal-potato rotations probably favored soil organic matter mineralization. Soil nitrates measured at mid-season were supplied by soil organic matter or organic residues mineralization [52,53]. Increases in NO_3N at mid-season in soils previously cropped to cereals and GM occurred at the period of greatest crop N needs, corresponding to the tuber bulking growth stage, which likely enhanced potato yield and N nutrition, as reported by Zebarth and Rosen [54].

Potato Yields and Tuber Specific Gravity

In 2009, total and marketable potato yields were significantly (p<0.01) affected by the preceding crops and by N fertilizer application rate, and showed no significant interaction between these main effects (Table 9). Contrast analysis showed that conventional rotations with cereals and summer or fall GMs enhanced total and marketable potato yields compared with continuous potato, and did not show significant difference among them. Total and marketable tuber yields were 32% and 34% (10.1 and 9.3 Mg ha^{-1}, respectively) greater in soils previously cropped to cereals and GMs than in soils under continuous potato. Our results are in agreement with numerous studies that found positive effects of crop rotations and GMs on potato production [53,55,56]. In all cases, total and marketable potato yields increased linearly with increasing N fertilizer rates (Table 9). This showed that after only a one-year rotation with cereals or GMs, soil N availability remained a limiting factor for potato yields.

Total and marketable potato yields were generally lower in 2011 than in 2009 (Tables 9 and 10), due to lower precipitations and drought that occurred in summer 2011 (Table 1). In 2011, total and marketable potato yields ranged from 23.2 and 42.3 Mg ha^{-1} and from 18.9 to 38.4 Mg ha^{-1} (Table 10), respectively, and were significantly increased (p<0.01) in soils previously cropped to cereals and GMs, and by N fertilizer addition. Data also showed a significant interaction between the preceding crops and N rates (p<0.05). Total and marketable potato yields increased in the following order: summer GMs>cereal-potato rotations>fall GMs> continuous potato. Increases in potato yields following GMs in 2011 were greater than those obtained in 2009 after

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Proceeding Crops	Total yield (Mg kg^{-1})	Marketable yield (Mg kg^{-1})	Specific gravity (g cm^{-3})	Black scurf incidence %
Continuous potato	31.4	27.2	1.0923	8
Barley	43	38	1.1003	6
Corn	37.2	29.9	1.0991	9
Oat	45.7	41.9	1.0951	11
Mustard	44.7	39.9	1.0972	2
Japanese Millet	40	33.7	1.0998	6
Pearl Millet	40.5	37.1	1.0983	4
Potato/mustard	33.3	28.1	1.0945	10
Potato/wheat	43.8	39.5	1.0853	14
Potato/Rye	42.2	37.9	1.0826	17
Potato/Oat	44.6	39.1	1.0819	12
Analysis of variance and contrasts (P value)				
Effect of the preceding crops	0.0051	0.0019	0.0274	0.0041
Effect of N fertilizer	0.0023	0.0037	ns	0.0452
Preceding crops × Nitrogen Fertlizer	ns	ns	ns	0.039
Linear effect of N	0.0055	0.0023	0.31	0.0274
Quadratic effect of N	ns	ns	ns	0.0419
Contrasts (Pr>F)				
Summer GMs£ vs. fall GMs	ns	ns	0.0061	0.0032
Summer GMs vs. cereal - potato rotations	ns	ns	ns	0.0029
Fall GMs vs. cereal-potato rotations	ns	ns	0.0028	ns
Green manures + cereal-potato rotations vs continuous potato	0.0043	0.0027	ns	0.0389

ns, not significant; Incidence of common scab was not detected in 2009.

£ GMs, green manures.

Table 8: Effects of cereal-potato rotation and green manures on potato yields and tuber specific gravity, and black scurf incidence in 2009.

only one rotation cycle. The highest overall total and marketable yields were achieved when potato followed pearl millet (12.2 and 14.4 Mg ha^{-1})and mustard (9.0 and 13.2 Mg ha^{-1} These findings provide evidence that pearl millet and mustard grown as summer GMs were the best preceding crops for maximizing potato productivity. Although japanese millet returned similar amounts of N and the residues had C: N ratio similar to pearl millet, it had a lower impact on potato yields, suggesting that factors other than N supply may explain the high performance of potato grown after pearl millet and mustard.

Lowest potato yields were obtained in 2011 in soils with fall GMs, compared with other rotation crops (Table 7) Fall GMs produced lowest biomass quantity and returned the least amounts of N to the soil particularly in 2010 where they provided less than 50% of those returned by summer GMs (Table 4). Dryer climatic conditions in 2011 also has not favored the fall green manure residues decomposition as they were incorporated in soil in late fall 2010 whereas summer GMs were incorporated in mid-August 2010. It has been shown that the rate and timing of organic N mineralization depends on soil moisture [57,58].

In 2011, potato yield response to N fertilizer application was quadratic (Table 10) contrary to 2009 where the N fertilizer effect was linear (Table 9), showing that N supply from the preceding crops to the following potato was more important in 2011 than in 2009, likely because the soil N supply was greater after the second cycle of rotation. This is consistent with many reports which showed that only a fraction of N from organic amendments becomes plant-available in the first year after incorporation [12] while their residual effects could last for 2-3 years due to the mineralization of accumulated N in soils [59]. Creamer and Baldwin [60] estimated that, in temperate regions, 9 to 29% of the added residues N is mineralized in the following crop cycle. Those findings demonstrate that using appropriate GMs and crop rotations could reduce or avoid N fertilizer inputs on subsequent potato crop, leading tolower N fertilizer costs as well as to lower risk of NON losses.

Positive effects on potato yields may also be attributed to soil properties improvement (Tables 5-8). Results of the present study suggest that benefits of cereal-potato rotations and GMs on potato yields could be related to increased N availability through crop residue mineralization, stimulation of soil microbial activity, and improved soil aggregation (Tables 6 and 7), which favored potato growth and N uptake. However, they also may be attributable to other factors not assessed in the present study. For example, Gasser et al. [5] related the positive effects of yearly fall rye and barley grown every 3 yr on the following potato yields and tuber specific gravity to improvement in soil water content at the critical flowering stage.

Tuber specific gravity

Potato specific gravity averaged between 1.0819 and 1.1003 g cm^{-3} in 2009, and from 1.0878 to 1.0945 g cm^{-3} in 2011 (Tables 9 and 10). In 2009, tuber specific gravity was significantly ($p<0.05$) affected by the preceding crops but not by N fertilizer application. Contrast analysis showed that tuber specific gravity was the lowest forpotato grown after fall GMs, while it did not differ among cereal-potato rotations and summer GMs (Table 9). In 2011, tuber specific gravity was significantly affected by the previous crops, N fertilizer, and their interaction (Table 10). As in 2009, the lowest tuber specific gravity values were observed for potato grown after fall GMs, while they were the highest for potato grown in cereal-potato rotations and following summer GMs. It could be inferred that N was provided later in 2011 cropping season by fall green manure decomposition which delayed potato maturity, resulting in lower tuber specific gravity [61]. Our results corroborate earlier studies in eastern Canada [55] and other investigations that reported that excess N decreases potato specific gravity, particularly during the tuber bulking growth stage [62].

Nitrogen uptake, nitrogen recovery, and nitrogen fertilizer efficiency

Potato N uptake and N fertilizer efficiency were in general lower in 2011 than in 2009, while apparent N recovery was similar in both years (Table 11). This is attributable to drier climatic conditions in 2011 than in 2009. However, the data indicate that potato N uptake was significantly increased by cereal-potato rotations and GMs, compared with continuous potato. In 2009, potato N uptake varied in the following order: summer and fall GMS>cereal-potato rotations>continuous potato. Potato N uptake increased linearly with increasing N fertilizer rates likely due to low N supply from the incorporated plant residues after one crop rotation cycle. There was a significant interaction between the preceding crops and N fertilizer rate on potato N uptake,

Proceeding Crops	Total yield	Marketable yield	Tuber Specific gravity (g cm^{-3})	Common Scab incidence %
Continuous potato	29.6	23.1	1.0916	3.49
Barley	32.1	26.4	1.0917	0.64
Corn	30.6	28.7	1.0945	0.46
Oat	32.8	28.4	1.0915	0.63
Mustard	38.4	38.4	1.0922	0.07
Japanese Millet	37.3	32.4	1.0924	0.42
Pearl Millet	42.3	35.4	1.0934	0.6
Potato/mustard	23.2	22.4	1.085	2
Potato/wheat	33.4	28.2	1.093	2
Potato/Rye	28.3	29.2	1.089	2.17
Potato/Oat	33.4	18.9	1.0878	1.83
Analysis of variance and contrasts (P value)				
Effect of the preceding crops	0.0025	0.0012	0.0036	0.0013
Effect of N fertilizer	0.0023	0.0062	0.0451	ns
Preceding crops × Nitrogen	0.0469	0.0281	0.0423	ns
Fertlizer Linear effect of N	0.0019	0.0037	0.0066	0.8
Quadratic effect of N	0.0026	0.0016	ns	ns
Contrasts (Pr>F)				
Summer GMs£ vs fall GMs	0.0025	0.0038	0.004	0.0325
Summer GMs vs cereal - potato rotations	0.0028	0.0059	ns	ns
Fall GMs vs cereal-potato rotations	0.0465	0.0033	0.0099	0.0468
Green manures + cereal-potato rotations vs continuous potato	0.0358	0.0472	ns	0.0048

£ GMs, green manures.

Incidence of black scurf was not detected in 2011

ns, not significant

Table 9: Effects of cereal-potato rotation and green manures on potato yields and tuber specific gravity, and common scab incidence in 2011.

demonstrating that these cropping systems helped to increased N fertilizer use by potato, likely due to improved soil conditions (Tables 5-8), which favored potato growth and N uptake. This finding is in accordance with other studies that reported synergistic beneficial effects of organic amendment and mineral N inputs on potato yields [56,63].

In 2011, potato N uptake was significantly increased by the preceding crops and N fertilizer application and no significant interaction between these two main effects was observed (Table 11). These results indicate that two rotation cycles with GMs provided significant amounts of available N to the following potato, whereas cereal-potato rotations increased potato N uptake probably due to their positive impact on soil properties (Tables 4 and 5), which likely favored soil organic N mineralization and availability (Table 4). Contrast analysis showed that higher N uptake occurred when potato succeeded summer GMs than cereals or fall GMs. Earlier studies showed that slow release of N from green manure residues are better synchronized with plant N uptake than inorganic N fertilizer [9,12,64], and could result in increasing N uptake efficiency. Therefore, discrepancies between preceding crops in this study may reflect poorer or better synchrony between N supply from residue decomposition with active potato N uptake. Under the cold temperate climate of Quebec (Canada), N'Dayegamiye and Tran [12] showed that incorporation of GMs such as millet and mustard to the soil in late summer or in early fall of the preceding year resulted in good synchrony between N release and timing of wheat N needs in the subsequent cropping season.

Potato apparent N fertilizer recovery averaged from 23% to 58% and from 29% to 57% in 2009 and 2011, respectively (Table 11). These values are consistent with other studies in eastern Canada where apparent N recovery in whole potato plant ranged from 29% to 77% [19,65]. Potato N use efficiency varied from 193 to 258 kg yield kg^{-1} N applied in 2009 and from 87 to 109 kg yield kg^{-1} N applied in 2011. In both years (2009 and 2011), potato apparent N recovery and N use efficiency were significantly increased by the preceding crops and N fertilizer application, and the interaction of the preceding crops and N fertilizer was significant (Table 11). This finding is consistent with other studies that reported enhanced potato apparent N recovery when combining GMs or other organic amendments such as manures or composts with mineral N fertilizer [56,64].

In 2009, potato apparent N recovery and N use efficiency decreased linearly with increasing N fertilizer rates, while the effect was quadratic in 2011, which again indicates a greater N supply from crop residues after the second cycle of rotation. Furthermore, increases of apparent N recovery and N use efficiency may reflect better synchronization between N release from green manure residues and potato N demands and thus, lower risk of N leaching losses [14,56]. In both years of the study, potato N uptake, apparent N recovery and N use efficiency were higher in soils previously cropped to summer GMs than cereals or fall GMS. This impact of summer GMS on N supply and N use efficiency may probably be related to greater N supply and to improved soil conditions which likely favored potato growth and N uptake.

Incidence of common scab and black scurf

Incidence of black scurf (*Rhizoctonia solani*) on potato varied between 2 and 17% in 2009 (Table 8), but was not detected in 2011.

	2009			2011		
Proceeding Crops	**N Uptake kg N ha^{-1}**	**Apparent N Recovery %**	**NFE kg yield kg^{-1} N**	**N Uptake kg N ha^{-1}**	**Apparent N Recovery %**	**NFE kg yield kg^{-1} N**
Continuous potato	119.3	33	193	97.5	29	89
Barley	135.6	40	228	105.6	29	87
Corn	140.3	49	202	98.4	48	102
Oat	144.1	35	216	116.7	34	92
Mustard	142.8	45	226	152.9	50	119
Japanese Millet	146.8	58	266	124	56	106
Pearl Millet	132.2	38	258	137	41	109
Potato/mustard	87.2	23	195	82.3	54	97
Potato/wheat	134.6	28	230	120.7	40	92
Potato/Rye	139.7	31	231	124.6	46	96
Potato/Oat	131.4	53	254	82.4	57	84
Analysis of variance and contrasts (P value)						
Effect of the preceding crops	0.0053	0.0398	0.0472	0.0013	0.0038	0.0046
Effect of N fertilizer	0.001	0.0453	0.0023	0.0021	0.0082	0.0061
Preceding crops × Nitrogen	0.0461	0.0463	0.0493	ns	0.0469	0.0457
Fertlizer Linear effect of N	0.0026	0.0383	0.0412	0.0031	0.0031	0.0018
Quadratic effect of N	ns	ns	ns	0.0057	0.0057	0.0013
Contrasts (Pr>F)						
Summer GMs£ vs. fall GMs	ns	0.0369	0.0458	0.0052	ns	0.0081
Summer GMs vs. cereal - potato rotations	0.0083	0.0312	0.0015	0.0019	0.0493	0.0048
Fall GMs vs. cereal-potato rotations	0.0425	ns	ns	ns	0.0484	ns
Green manures + cereal-potato rotations vs continuous potato	0.0319	0.0495	0.0037	0.0459	0.0488	0.0057

£ GMs, green manures.

ns, not significant

Table 10: Effects of cereal-potato rotation and green manures on potato N uptake, apparent N recovery, and N use efficiency (NFE).

Conversely, common scab (*Streptomyces scabies*) was not detected in 2009 while its incidence varied from 0.13 to 3.49% in 2011 (Table 9). These opposite trends for common scab and black scurf between the two cycles of rotations were probably related to different environmental conditions since R. solani was favored by low temperature in the cropping season of 2009 (Table 1) as showed by Harrison [66], while *S. scabies* was promoted by high temperature in 2011 and low levels of precipitation (Table 1) as recorded by Loria et al. [67]. The incidence of black scurf was significantly influenced by the preceding crops and N fertilizer application, and the interaction was significant (Table 8). Orthogonal contrast analysis showed that N fertilizer application had a significant linear effect ($P<0.05$) on the incidence of black scurf on potato. Contrast analysis showed that the incidence of black scurf in 2009 increased in the following order: fall GMs> continuous potato=cereal-potato rotations>summer GMs (Table 8). In 2011, the incidence of common scab was significantly ($P<0.01$) affected by the preceding crops, and was higher for fall GMs, compared to other rotational crops (Table 9).

Data obtained in the present study are in accordance with previous investigations which showed that 2 or 3 yr cereal- potato rotations and GMs can reduce the occurrence of potato diseases, including black scurf [17,68,69] and common scab [16]. In the present study, the lowest incidence of black scurf and common scab was recorded for potato grown after summer GMs (mustard, japanese millet, and pearl millet). The suppressive effects of these green manure crops on potato black scurf and/or common scab have been demonstrated in various studies reporting the control of potato diseases with pearl millet [70], japanese millet [68], and mustard [15,17]. As shown in the present study, these green manures also increased soil microbial activity (Table 6) which may result in increased competition for existing nutrients [18,71] or increased populations of antagonistic organisms against *S. scabies* [71,72] or *R. solani* [15]. The suppressive effects of mustard and other Brassica spp. are often attributed to their high contents in glucosinolates [15-17]. Cereals used in the present study included barley, corn and oat which have been recognized to suppress potato diseases [73]. Our results revealed that the cereals significantly reduced the incidence of common scab and black scurf, compared with fall GMs and continuous potato. Increases of black scurf incidence and common scab in response to fall GMs suggest that these organic materials incorporated late in the season were still decomposing during the following season, and likely stimulated soil microorganisms including *R. solani* and *Rhizoctonia solani*.

Economic returns

Gross margins and net returns (Table 11) were maximized in potato cropping systems including fall GMs, whereas they were the lowest for rotation systems with cereals and summer GMs. In the 2008-2009 rotation cycle, fall GMs increased total net returns by 11% to 28%, representing \$1775 to \$4567 ha^{-1}, compared to those generated by continuous potato. The overall net benefit however doubled in the

	2008-2009			2010-2011		
Rotation	**Crop Value**	**Total Variable Cost**	**Total net return**	**Crop Value**	**Total Variable Cost**	**Total net return**
Continuous potato	16070	5544	10526	15203	6154	9049
Barley-potato	9788	3714	6074	9988	3906	6082
Corn-potato	8617	4179	4438	12534	4148	8386
Oat-potato	10895	3702	7193	10877	3884	6993
Mustard-potato	8213	3671	4542	12600	3839	8761
Japanese millet-potato	10146	3697	6449	13316	3796	9520
Pearl millet-potato	10732	3741	6991	13748	3644	10105
Potato/mustard-potato	18190	5653	12538	18741	6493	12248
Potato/wheat-potato	17845	5613	12233	19230	6694	12536
Potato/rye-potato	20637	5709	14929	22497	6830	15667
Potato/oat-potato	20107	5630	14478	22104	6488	15616

Gross margins were calculated based on crop yields means in each treatment

Table 11: Economic metrics for two consecutive 2-yr potato rotation cycles with cereal and green manures.

2010-2011 rotation cycle, when fall GMs increased net returns by +23% to +48%, representing a gain of $3199 to $6618 ha^{-1} over those generated by continuous potato. In both crop rotation cycles, potato rotations including rye and oat as fall GMs were the most economically profitable. The high profitability of potato rotations with fall GMs is related to potato being harvested on all years, contrary to the systems including cereals or summer GMs.

By contrast, rotation systems with cereals and summer GMs reduced total net benefit by 32% to 57%, representing $5175 to $7453 ha^{-1} compared with continuous potato. Cereal-potato rotations were less profitable than continuous potato due to the low value of cereal products compared with that of potato. The low net returns obtained with summer GMs were explained by the lack of cash crop during the first year of each 2 y rotation cycle. Our results agree with finding by Snapp et al. [14] who showed that growing green manure crops during regular cash crop season reduce the profitability due to the lack of marketable output on that particular year. However, net returns obtained with summer GMs were increased in 2011 compared with the first rotation cycle (2008-2009). In 2009 and 2011, net returns with summer GMs represented 50 and 70% of those obtained with fall green manures, respectively. Although net returns for fall GMs remained higher than for the other cropping systems tested, including fall GMs may be non- profitable as it was demonstrated that it reduced tuber specific gravity and increased the incidence of common scab and black scurf (Tables 9 and 10). As fall GMs are cultivated on all years after potato harvest, this crop system may also deteriorate soil properties and productivity. After two consecutive 2 yr rotation cycles (2008-2011), potato yields obtained with fall GMs were lower than with summer GMs. Therefore, rotation systems with summer GMs may become more profitable than continuous potato with or without fall GMS on the longer term.

Conclusion

Including cereals and GMs in potato rotation is expected to improve soil properties and boost potato yields and quality. Crop rotation systems including cereals (oat, barley and corn), summer GMs (mustard, Japanese millet and pearl millet) and fall GMs (mustard, wheat, rye and oat) increased total and marketable potato yield, compared to continuous potato. Summer GMs and cereals as preceding crops supported higher potato yield and greater N nutrition than fall GMs, which was attributed to higher N input by summer GMs and to improvement of soil properties (soil NO_3^- concentration, microbial and enzymatic activities, soil structure). Even if cereals and fall GMs also improved soil properties significantly, their impact on potato yields and N nutrition was less than summer GMs because of their low N input. It remains challenging to design crop rotations to build soil health and sustain potato productivity, but growing cereals or summer GMs in rotation with potato is an interesting alternative to improve soil properties while sustaining potato yield and quality. Including fall GMS in potato rotation will have a small impact on potato yield and soil properties, compared to summer GMs and cereals as preceding crops. Moreover, fall GMs produced potato with lower specific gravity and they induced common scab and black scurf incidence disease. Fall GMs permit more frequent potato cultivation, compared to summer GMs and cereals, but they cannot restore soil properties to the same extent. In the cold humid temperate regions of eastern Canada, fall GMs produce lower biomass and add less N to soil, which contributes less to potato yield and N nutrition, compared to summer GMS. Results showed that continuous potato production with fall GMs even though profitable may not represent a viable option to sustain potato production and soil quality on the longer term. Since farmers prefer to include cash crops in the potato rotation or plant a fall GM after potato harvest, attention must be paid to the choice of fall GM species and consider a longer potato rotation to avoid frequent cultivation of potato, which causes a deterioration in soil properties and increases disease incidence.

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