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Manure and Paper Mill Sludge Application Effects on Potato Yield, Nitrogen Efficiency and Disease Incidence

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Abstract: Appropriate organic amendment management is essential in potato production to increase soil productivity and potato (*Solanum tuberosum* L.) quality. The objectives of this two-year field study (2004–2005) were to evaluate the effects of organic amendment applications with or without mineral N fertilizer addition on potato yield, N uptake, N use efficiency (NUE), and on disease incidence. The experimental design was a split-plot, which included nine treatments with four different organic amendments applied in fall 2003 or in spring 2004 at a rate of 40 Mg ha^{-1} (wet basis) and an unamended control in main plots, and N fertilizer rates (0 and 90 kg N ha^{-1}) in sub-plots. Organic amendments consisted of fresh cattle manure (FCM), composted cattle manure (CCM), paper mill sludge with C/N ratio <15 (PMS$_1$) and paper mill sludge with C/N >15 (PMS$_2$) applied alone (0 kg N ha^{-1}) or supplemented with mineral fertilizer at a rate 90 kg N ha^{-1}. The N fertilizer rate in the unamended control consisted of 0 and 150 kg N ha^{-1}. No organic amendments were applied in 2005 to evaluate residual effects. Fall and spring applications of FCM, CCM and PMS alone significantly increased N uptake and potato marketable yields by 2.5 to 16.4 Mg ha^{-1}, compared to the unfertilized control. Combining organic amendments with N fertilizer at 90 kg N ha^{-1} increased potato yields, N uptake, and specific gravity, which were comparable to those obtained in mineral N fertilizer

treatments (150 kg N ha^{-1}). Residual effects of organic amendments alone had no significant effects on potato yields or on N uptake compared to the unfertilized control. Potato NUE for FCM, CCM and PMS ranged from 6% to 25% in the first year and from 2% to 8% in the residual year. The NUE values were higher for PMS with lower C/N ratio compared to FCM and CCM. This study did not show any difference between organic amendment applied in spring or fall on potato yield and quality. It was also demonstrated that mineral N fertilizer needed to be combined with organic amendments to sustain potato yield and N nutrition. This study showed that appropriate organic amendment management could increase potato yield and quality and reduce N fertilizer requirement.

Abbreviations

FCM: fresh dairy cattle manure
CCM: composted dairy cattle manure
MF: mineral N fertilizer
NUE: nitrogen use efficiency
FNE: fertilizer nitrogen equivalency
PMS$_1$: paper mills sludge with a C/N ratio <15
PMS$_2$: paper mill sludge with a C/N ratio >15

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1. Introduction

Regular application of organic amendments can sustain soil N fertility and increase potato yields. Dairy cattle manure and paper mill sludge application improved soil physical and biological properties and increased corn yields and N availability [1]. Canali *et al.* [2] reported that farmyard manure and compost applications sustained potato yield. These authors showed that green manures and organic amendments might provide a valid alternative to the conventional mineral N fertilizer mitigating potential environmental risks due to N leaching. Thus, potato crop presents a great potential for receiving animal manures and paper mill sludges. Approximately a million tons of paper mill sludges and more than 30 million tons of animal manures are applied annually on the soils of the province of Quebec, Canada [3].

Better use of organic amendments requires however knowledge of their N use efficiency as it is important that N released from animal manures or organic amendments meet potato N requirements. Lower N supply or efficiency can lead to nutrient deficiency and poor growth and yield, respectively, whereas excessive N supply from organic amendments may induce excessive vegetative growth and low yields and quality [4,5]. A better N optimization from organic amendments can be achieved with knowledge of the organic material nitrogen release rates [3,6,7] and additional mineral N fertilizer N additions may be needed to satisfy crop needs. The N availability or N use efficiency of manure or

other organic amendments is lower than that of mineral N fertilizer [3,6]. Nitrogen from organic amendments is mostly in organic form and must be mineralized to become available to crops. The N availability is affected by their chemical composition that is characterized by total N and C/N ratio [3,8,9]. Chadwick *et al.* [9] established that 40% of the variation in the N mineralization rate of manure was explained by the C/N ratio. Fast N mineralization and availability is expected for organic fertilizers with low C/N ratio (<15) [3,10]. The PMS with C/N ratios below 15 decompose quickly in the soil during the first year of the application and N released is readily available to the crop [3].

Nitrogen use efficiency from organic amendments also depends on the crop species. Long-season crops such as potatoes and grain corn will use more mineralized N from organic materials compared with short period crops such as cereals [3,8,11]. The application timing also influences the nitrogen use efficiency [12,13]. Although fall application of organic materials is likely to be associated with economic and logistic advantages including time saving, it is also at higher risk of N losses associated with leaching or denitrification that occurs during fall and early spring [11,13]. On the other hand, spring application of organic amendments can increase soil compaction because of wet soil conditions [14]. Several studies investigated advantages of fall *versus* spring application of manure and organic materials on corn yield. Solid swine manure fall application increased corn yield compared to spring application [12,13,15,16]. Hansen *et al.* [13] reported that fall and spring application of solid dairy cattle manure gave similar barley (*Hordeum vulgare* L.) yield and N uptake.

The main challenge in managing organic amendments for potato nutrition is to match N release with the crop N demand. The potato crop requires much N in the early season, between 65 and 75 days after planting [17]. The N availability from organic amendments may not be concomitant with the crop N demand period. Therefore, to meet crop N needs, organic amendments application has to be supplemented with N fertilizer although nitrogen surplus can occur when highly mineralizable organic materials are applied at high rates and are combined with mineral N fertilizer. This may promote excessive vine growth, resulting in delayed tuber bulking and maturation, low specific gravity and higher levels of reducing sugars in tubers.

The use of organic amendments in potato production can also influence potato disease incidence [18]. The role of fresh or composted organic materials in reducing soil-borne diseases for potato, corn and bean has been reported by Darby *et al.* [19], Olanya *et al.* [18] and Hoitink and Fahy [20]. It was hypothesized that organic amendments application may stimulate soil microbial activity and reduce the impact of soil-borne pathogens on crops, as a result of greater competition [18–21]. Other studies showed that applying farmyard manure and liquid swine manure to potato reduced scab and black scurf severity [22,23].

Improved organic amendment management requires knowledge of their N use efficiency to maintain potato quality, as excessive N availability may reduce potato quality and increase disease incidence. The objectives of this two-year study were to evaluate the effects of solid dairy cattle manures, paper mill sludge application and mineral N fertilizer addition on potato yield and quality, and N use efficiency in the year of application and in the subsequent year. We also determined the effect of these organic amendments on common scab and black scurf incidences.

2. Materials and Methods

2.1. Field Site and Organic Materials

The experiment was carried out in 2004 and 2005 in a field of the Research and Development Institute for the Agri-Environment (IRDA) located in Deschambault, near Québec City, Canada (46°34′ N, 71°13′ W). The soil is a Batiscan densic podzol (sandy over clayey, mixed, nonacid, frigid, Aeric Humaquet) which corresponds to orthic podzol for FAO classification). The particle-size distribution of the A horizon (0–20 cm) was 820 g sand kg^{-1}, 50 g silt kg^{-1}, and 130 g clay kg^{-1}. The initial pH (H_2O) was 6.5 and the soil C and N contents were 21.2 and 2.2 $g \cdot kg^{-1}$, respectively. The soil available P and K contents were 381 and 274 $mg \cdot kg^{-1}$, respectively.

Fresh dairy cattle manure (FCM) and dairy cattle manure compost (CCM) were collected from a Quebec Ministry of Agriculture experimental dairy farm station, and paper mill sludges were obtained from the Abitibi-Bowater paper mill located at Donnacona, near Québec, Canada. The FCM and CCM contained on average 303 g kg^{-1} dry matter, 412 $g \cdot kg^{-1}$ C, 19 $g \cdot kg^{-1}$ N, 24 $g \cdot kg^{-1}$ P, and 69 $g \cdot kg^{-1}$ K (Table 1). The paper mill sludges (PMS) used contained 194 $g \cdot kg^{-1}$ dry matter, 443 $g \cdot kg^{-1}$ C, 34 $g \cdot kg^{-1}$ N, 10 $g \cdot kg^{-1}$ P and 59 $g \cdot kg^{-1}$ K. The C/N ratio ranged from 8.0 to 30 depending on the organic materials. The PMS applied contained less P and K compared to dairy cattle FCM or CCM.

Table 1. Physical and chemical properties * of organic amendments applied in fall 2003 and in spring 2004.

Application time	Organic amendments	DM g·kg^{-1}	Organic C g·kg^{-1}	Total N g·kg^{-1}	N ha^{-1} kg [†]	P mg·kg^{-1}	K mg·kg^{-1}	C/N
Fall 2003	PMS$_1$	144	440	55.0	317	13.7	6.2	8
	PMS$_2$	229	460	20.9	191	8.9	4.5	22
	FCM	386	399	13.6	210	30.6	73.8	30
	CCM	377	402	22.5	339	43.8	104.2	18
Spring 2004	PMS$_1$	151	432	37.9	229	8.6	3.8	11
	PMS$_2$	251	439	21.3	214	7.9	4.1	20
	FCM	261	447	22.0	230	13.2	50.4	20
	CCM	189	400	20.2	153	8.3	46.3	20

FCM: Fresh cattle manure; CCM: composted cattle manure; PMS$_1$: paper mill sludge with C/N <15; PMS$_2$, paper mill sludge with C/N of >15; DM, dry matter; * Organic C and nutrient contents are referred on dry matter basis; [†] Total N applied with 40 Mg ha^{-1}.

2.2. Experimental Design

The experimental design was a split-plot with organic amendments in main plots and mineral N fertilizer rates in sub-plots (0 and 90 kg N ha^{-1}). The study included nine treatments in main plots with four different organic amendments applied in fall 2003 or in spring 2004 at a rate of 40 Mg ha^{-1} (wet basis) and an unamended control. Treatments with organic amendments consisted of fresh cattle manure (FCM), composted cattle manure (CCM), paper mill sludge with C/N ratio <15 (PMS$_1$) and paper mill sludge with C/N >15 (PMS$_2$) applied alone (0 kg N ha^{-1}) or supplemented with mineral fertilizer at a rate of 90 kg N ha^{-1}. The N fertilizer rate in the unamended control consisted of 0 and

150 kg N ha^{-1}. Mineral N fertilizer rate recommended in eastern Canada is 150 kg N ha^{-1} for potato in fertilizer management guidelines. Nitrogen fertilizer supplemented to organic amendment was reduced at 90 kg N ha^{-1} to avoid excessive N, which may induce pest incidence and reduce potato yield quality (specific gravity). Results obtained for corn in the same climatic conditions showed that nitrogen release for manure and paper mill sludges was about 25% which represents 60 to 90 kg N ha^{-1} depending on organic material types [3]. Corn and potato have a long growth period and present similar N needs for growth.

The plot size was 6 m wide and 12 m long. No additional organic amendments were applied in 2005 to evaluate residual effects. The organic amendments were surface applied to different plots with a manure spreader on 23 October 2003 and 20 May 2004 and immediately rototilled into the soil into a depth of about 10 cm. Calcium ammonium nitrate (27-0-0) was the source of inorganic N fertilizer, which was applied at 90 kg and 150 kg N ha^{-1} in amended and unamended treatments, respectively. Prior to planting, each plot received a base application of 75 kg P_2O_5 ha^{-1} as superphosphate, and 75 kg K_2O ha^{-1} as muriate of potassium based on soil analysis. Potato tubers (cv. Chieftain) were planted in the last week of May 2004 and 2005 with a 35 cm in-row spacing and distance of 91.5 cm between rows, resulting in a crop density of 45,000 plants ha^{-1}. Pesticide management was as recommended in Quebec for potato crop.

2.3. Analytical Methods

Potato tubers were hand-harvested from two 12-m row sections of a middle row from each plot. The harvested tubers were graded in the following categories: Large (7.9–11.4 cm) and Canada No.1 (5.1–7.9 cm). The small (<5.1 cm) and deformed tubers were also recorded. A representative 4-kg sample of tubers from each plot was used for determination of tuber dry matter, specific gravity, N content and diseases. Six 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 0.15 mm for the 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* Kuhn). 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% [22]. Severity of common scab and black scurf was measured as an index calculated by counting the number of tubers ($n = 50$) falling in classes 0 to 6. The number in each class was multiplied by the class number and summed.

For organic amendments, dry matter content was analyzed from weight loss by oven drying at 70 °C; pH was determined in 0.01 M $CaCl_2$ in 1:2 (w/v) organic material: solution ratio, total C by loss on ignition; total N by dry combustion (CNS-1000, LECO Corporation, St-Joseph, MI, USA); total P and K by wet digestion in H_2SO_4-H_2O_2 [24]. The P concentration in the extracts was determined colorimetrically (Hitachi U-1000, Tokyo, Japan) using the molybdate reaction, whereas the K concentration was determined by flame absorption spectroscopy (Perkin-Elmer 503, Überlingen,

Germany). Soil total C was determined by the Walkley-Black method [25] and N by Kjeldahl digestion [26]. Total C content was considered to represent organic C because this soil does not contain carbonates. Extractable P and K were determined in a Mehlich III solution [27]. Total N levels were measured using an Automated Technicon Autoanalyzer (Model AAII, Technicon Instruments, Tarytown, NY, USA) and mineral elements (P, K) using an inductively coupled plasma optical emission spectrometer (Perkin Elmer 4300 DV, Boston, MA, USA; Model AAII, Technicon Instruments, Tarytown, NY, USA). Particle size analysis was performed on air-dried soils by the pipette method after the destruction of organic matter with H_2O_2 and dispersion with sodium hexametaphosphate [28]. Soil pH was measured in 1:1 soil:water solution.

2.4. Calculations

Nitrogen use efficiency (NUE) reflects the amount of applied nitrogen recovered by tubers. Data obtained on potato N uptake in 2004 and 2005 were used to determine apparent N use efficiency for mineral N fertilizer (150 kg N ha^{-1}) and organic N amendments. The apparent NUE was calculated following the method used by Zvomuya *et al.* [29]:

$$NUE = (Ntreat - Ncontrol) \times 100/N \text{ applied} \tag{1}$$

where Ntreat represents the amount of nitrogen accumulated in the tubers for a given fertilizer treatment (organic amendment or mineral N fertilizer); Ncontrol is the amount of N removed by tubers in the unfertilized control plots (0 kg N ha^{-1}); N applied is the total N applied with mineral or organic amendments.

Nitrogen efficiency for applied organic amendments refers to fertilizer N equivalency. The fertilizer N equivalency (FNE) was estimated as follow:

$$NUE_{OA} \times 100/NUE_{NF} \tag{2}$$

where NUE_{OA} is the apparent N use efficiency in the treatments with organic amendment application and NUE_{NF} in the treatment with N fertilizer application.

2.5. Statistical Analysis

To assess the effects of treatments on the response variables, a normal mixed model was fitted to the data using the PROC MIXED procedure of SAS [30]. The fixed effects were the treatments of organic amendments, the N fertilizer level and the interaction organic amendment × N fertilizer. The random effects were the blocks, the whole-plot error and the residual error. The random effects were assumed to be independent and normally distributed with mean zero and constant variance σ^2_b for the blocks, σ^2_w for the whole-plots and σ^2_e for the residual errors. The F-tests for fixed effects of the analysis of variance table were considered.

3. Results and Discussion

3.1. Rainfall and Temperature at Studied Site in 2004 and 2005

Total monthly rainfall and average monthly temperature were different in both years (Figure 1). Year 2004 had more rain early in the growing season (May and June) than 2005 and the reversed was observed toward the end of the growing season where year 2005 showed higher rainfall than 2004. On the other hand, year 2005 was warmer than 2004 during the whole growing season.

Figure 1. Monthly precipitation and average monthly temperature at studied site.
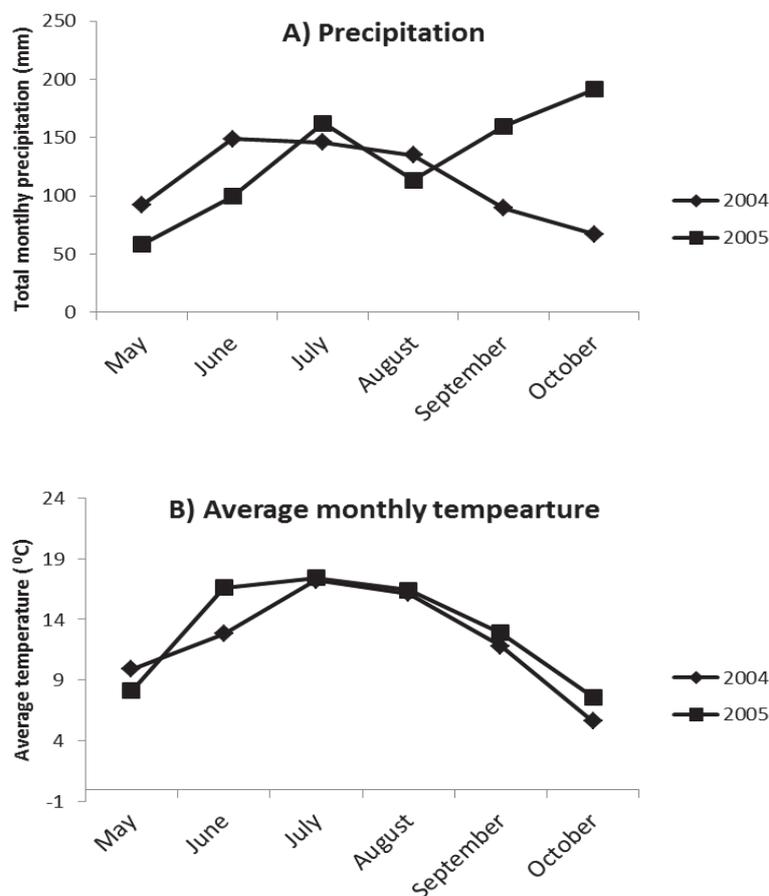
Data were from St. Camille meteorological station, Quebec (46°29′00,000″N; 70°13′00,000″O).

3.2. Potato Yields, N Uptake and Specific Gravity

In 2004, organic amendment application significantly increased the total and marketable yield, and there was a significant interaction between organic amendments and N fertilizer ($P < 0.001$) (Table 2 and Figure 2A,C). Organic amendments applied alone increased total and marketable yields by 3.6 to 17.2 Mg ha^{-1} and by 2.5 to 16.4 Mg ha^{-1} respectively, compared with the unamended and unfertilized control. Potato yields were increased by 11.3% to 54.3% when organic amendments were combined with N fertilizer, compared with organic amendments applied alone. Potato yields with mineral N fertilized plots (150 kg N ha^{-1}) were comparable or greater than those obtained with organic amendments supplemented with 90 kg N fertilizer ha^{-1} (Figure 2A,C). When applied alone, fresh and

composted dairy cattle manure (FCM and CCM) gave lower potato yields than PMS_1 and PMS_2 but the opposite was observed when they were supplemented with N fertilizer (Figure 2A,C). This is probably due to excessive N from applied PMS and N fertilizer, which can lead to excessive vegetative growth and low yields as also was reported by Ojala *et al.* [4] and Porter *et al.* [5] for nitrogen fertilizer. In fact, the N content in dairy cattle manure was lower than that of PMS_1 (Table 1).

Table 2. Analysis of variance of the effects of organic amendment application with or without reduced N fertilizer on potato yield, N uptake and disease incidence (*P* values).

| Treatments	Total yield	Marketable yield	DM	Specific gravity	N uptake	Common scab	Black scurf
2004							
Organic amendment	0.0164	0.0142	0.8883	0.0183	0.0462	0.1348	0.2092
N fertilizer	<0.0001	<0.0001	0.1036	0.0430	<0.0001	0.0136	0.0192
Organic × N fertilizer	<0.0001	<0.0001	0.1468	0.0847	<0.0001	0.4538	0.7936
2005							
Organic amendment	0.3529	0.3610	0.9816	0.1398	0.5187	0.3321	0.2154
N fertilizer	<0.0001	<0.0001	0.8030	0.0009	<0.0001	0.8714	0.1261
Organic × N fertilizer	0.4845	0.5935	0.2665	0.4256	0.2991	0.1322	0.4453

In 2005, we determined the residual effect of organic amendments on potato yield, and no effect of organic amendments was observed. (Table 2, Figure 2B,D) while the effect of N fertilizer application was highly significant (*P* < 0.0001). Residual effects of organic amendments applied alone were negligible as potato yields obtained from these treatments were comparable to those in the unamended and unfertilized control (Figure 2B,D). Paper mill sludges alone gave yields comparable to those of unamended and fertilized treatment (150 kg N ha^{-1}) in 2004 but were comparable to those in unamended and unfertilized control (0 kg N ha^{-1}) in 2005. The low C/N ratio associated with PMS implies rapid N decomposition and negligible residual N effects in the subsequent years as reported previously by N'Dayegamiye [3]. These results suggest that for organic amendments with low C/N ratio (C/N < 30) the application of N fertilizer is required in the residual year to sustain crop N needs.

Potato N uptake varied from 98 to 179 kg N ha^{-1} in 2004 and from 85 to 214 kg N ha^{-1} in 2005 (Figure 3A,B). Organic amendments and mineral fertilizer significantly increased potato N uptake in 2004 (*P* = 0.0462 and *P* ≤ 0.0001, respectively) compared with the unamended and unfertilized treatments (Table 2). The interaction of organic amendment and N fertilizer was also significant on potato N uptake. During the two years of the study, the combination of organic amendment with mineral N increased N uptake by an average of 105% compared with organic amendment applied alone. As for potato yields, synergic effects of organic amendments with mineral N fertilizer on N uptake were important (*P* < 0.0001). These results show that additional mineral N fertilizer is necessary to satisfy crop N nutrition following organic amendments application. Most of the N in CM or PMS is in organic form and needs to be mineralized to be available to the crop.

No difference in potato yield and N uptake was found between fall or spring manure and paper mill sludge application (Figure 3A,B). Our results are similar to those obtained by Hansen *et al.* [13], Thomsen [16] and MacLeod *et al.* [31] where fall or spring application of dairy cattle manure gave similar barley and corn response.

In 2004, the specific gravity of tubers in plots amended with organic amendments ranged from 1.070 to 1.073 (Figure 3C), and was significantly increased by organic amendment and mineral fertilizer application (Table 2). The interaction of organic amendment and N fertilizer was not significant. In general, higher values of tuber specific gravity were observed in 2005 than in 2004 (Figure 3C *versus* Figure 3D). Optimum moisture availability as tubers approach maturity can increase specific gravity and our results could probably be explained by the fact that precipitation and temperature were higher in 2005 during September and October than in 2004 (Figure 1A).

Figure 2. Effects of mineral N fertilization and organic amendments with or without N fertilizer (N) on total (**A**, **B**) and marketable yield (**C**, **D**) in 2004 and 2005, respectively.
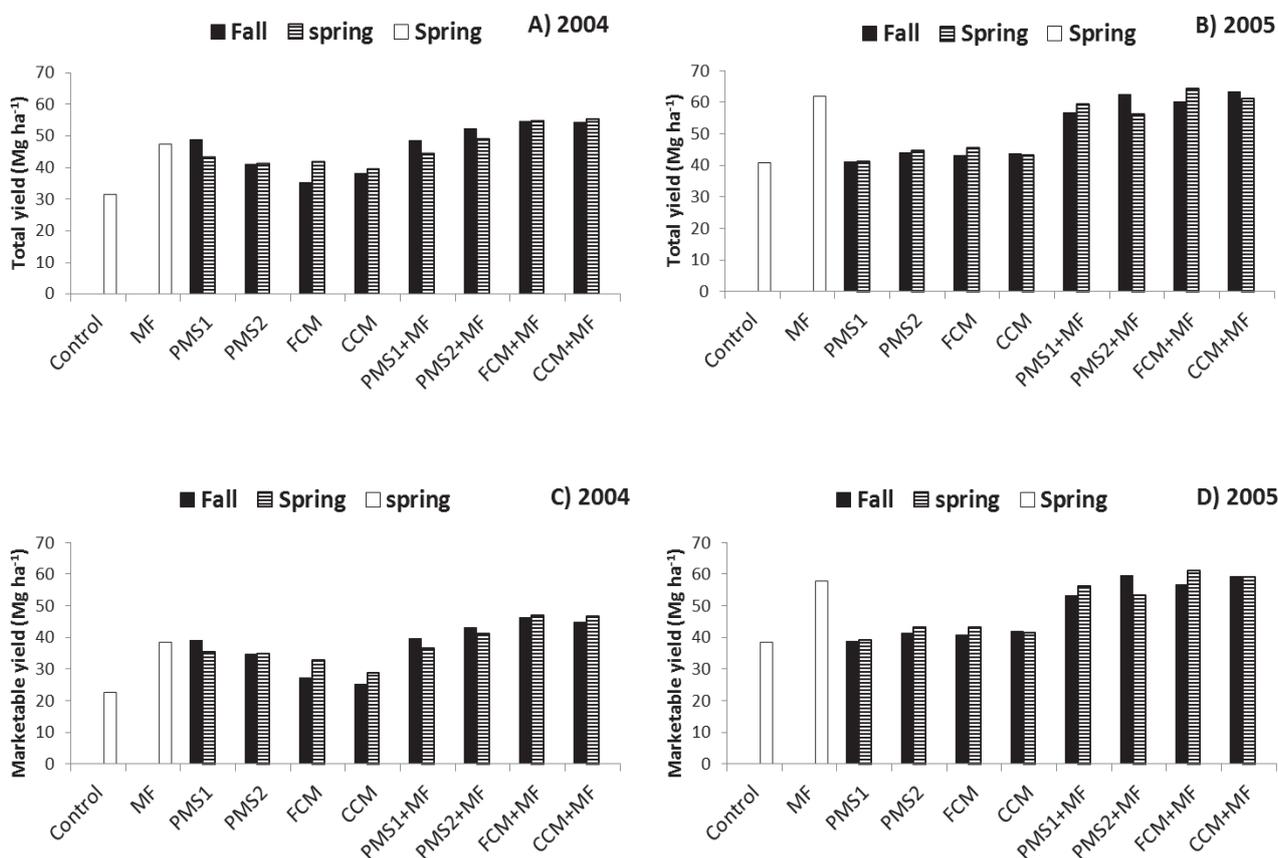
Control: non N fertilizer was applied; MF: mineral fertilizer applied at 150 kg N ha^{-1}; PMS$_1$: paper mill sludge with C/N <15; PMS$_2$: mixed paper mill sludge with C/N of 20; FCM: fresh dairy cattle manure; CCM: composted dairy cattle manure; PMS$_1$ + FM, PMS$_2$ + MF, FCM + MF, CCM + MF refer to PMS$_1$, PMS$_2$, FCM, and CCM supplemented with mineral fertilizer at a rate of 90 kg N ha^{-1}.

Figure 3. Effects of mineral N fertilization and organic amendments with or without N fertilizer (N) on total and N uptake (**A**, **B**) and specific gravity (**C**, **D**) in 2004 and 2005.
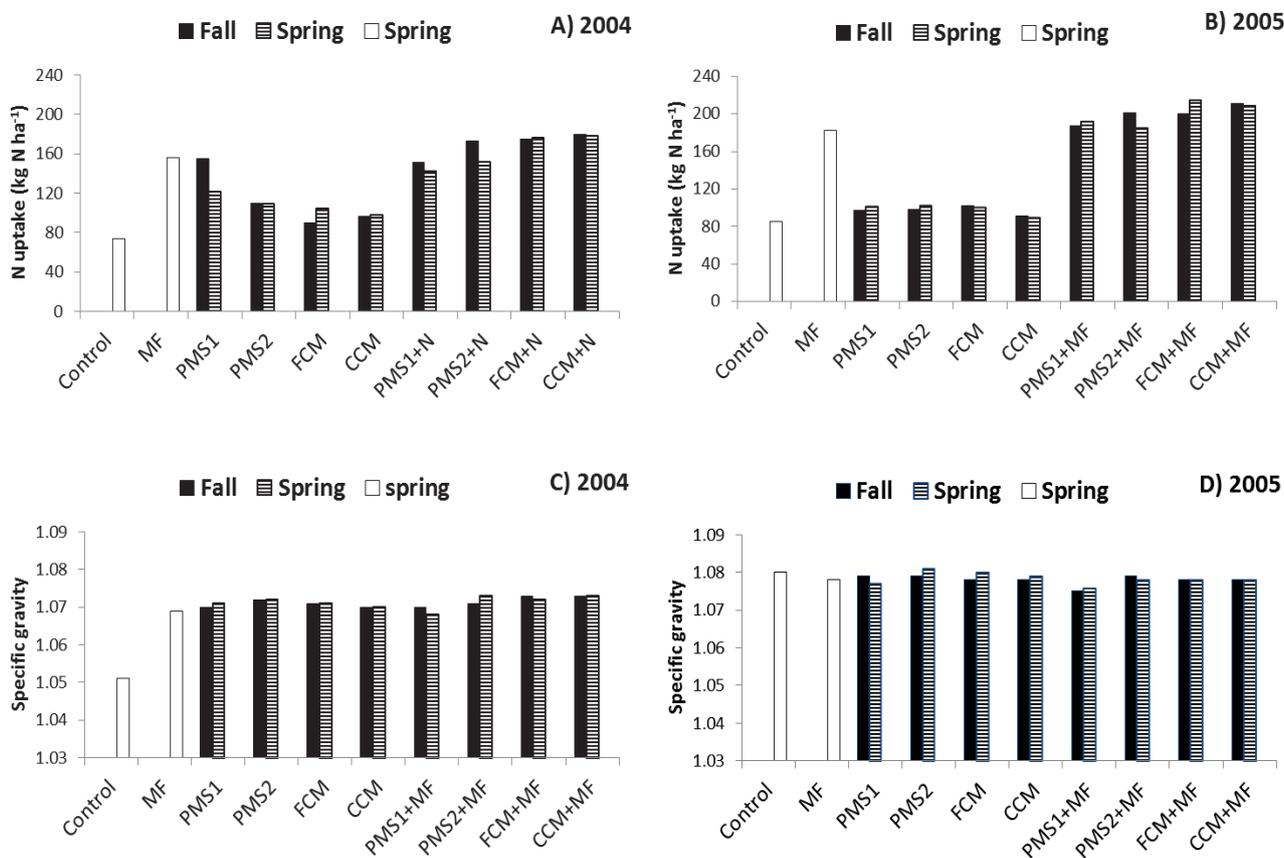
Control: non N fertilizer was applied; MF: mineral fertilizer applied at 150 kg N ha^{-1}; PMS$_1$: paper mill sludge with C/N <15; PMS$_2$: mixed paper mill sludge with C/N of 20; FCM: fresh dairy cattle manure; CCM: composted dairy cattle manure; PMS$_1$ + FM, PMS$_2$ + MF, FCM + MF, CCM + MF refer to PMS$_1$, PMS$_2$, FCM, and CCM supplemented with mineral fertilizer at a rate of 90 kg N ha^{-1}.

3.3. Nitrogen Use Efficiency (NUE) and Fertilizer N Equivalency (FNE)

The NUE of the organic amendment treatments ranged from 13% to 25% and was lower compared to mineral fertilized treatment (54%) (Table 3). Among organic amendments, PMS$_1$ exhibited the highest NUE (20% and 25%) while FCM and CCM had the lowest NUE. The PMS$_2$ had intermediate NUE values, which were higher than those of FCM and CCM. The relatively low NUE of fresh and composted manures (Table 3) are probably related to their stable and less available organic N, as demonstrated also by potato lower yield and N uptake. The bedding material used in dairy farm was sawdust, which produces less decomposable N.

Table 3. Potato N use efficiency and fertilizer N equivalency in the first year of organic amendment application (2004).

Application time	Organic amendment	Total N inputs (kg ha^{-1})	N uptake (kg ha^{-1})	NUE (%)	FNE (%)
Fall 2003	PMS$_1$	317	155	25	46
	PMS$_2$	191	109	18	33
	FCM	210	90	8	15
	CCM	339	96	6	10
Spring 2004	PMS$_1$	229	121	20	37
	PMS$_2$	214	108	16	30
	FCM	230	104	13	24
	CCM	153	97	15	28
N fertilizer		150	155	54	100.0
Control		0	74	…	

FCM: Fresh cattle manure; CCM: composted cattle manure; NUE: Apparent N use efficiency; FNE: fertilizer N equivalency; PMS$_1$: paper mill sludges with C/N <15; PMS$_2$: paper mill sludges with C/N of 20.

The FNE in the first year of application followed this order: PMS$_1$ > PMS$_2$ > FCM and CCM independently of application time (Table 3). Generally, the PMS had the highest FNE with average values of 41% and 31% for PMS$_1$ and PMS$_2$, respectively. These results corroborate findings of N'Dayegamiye [3] and Vagstad *et al.* [32] who reported net N mineralization and high N availability of PMS in the first year of application. The FNE of FCM and CCM were lower than that of PSM. As reported above for NUE, the higher FNE of PMS is associated with low C/N ratio. This result is in line with the finding of Douglas *et al.* [11] in an experiment with barley where FNE was negatively related to the C/N ratio of the organic amendments. In the residual year, values of NUE varied from 2% to 8% (Table 4). Values of FNE in the residual year (2005) ranged from 3% to 13% (Table 4) compared with values ranging from 10% to 46% in 2004 (Table 3). Similarly to NUE, the FNE values were higher for PMS than for FCM and CCM in the residual year.

Table 4. Potato N use efficiency and fertilizer N equivalency in the residual year of organic amendments application (2005).

Application time	Organic amendment	Total N inputs (kg ha^{-1})	Residual year N uptake (kg ha^{-1})	NUE (%)	FNE (%)
Fall 2003	PMS$_1$	317	97	4	6
	PMS$_2$	191	98	6	10
	FCM	210	102	8	13
	CCM	339	91	2	3
Spring 2004	PMS$_1$	229	101	7	11
	PMS$_2$	214	101	8	13
	FCM	230	100	6	10
	CCM	153	88	2	3
N fertilizer		150	183	60	100.0
Control		0	85	…	

FCM: Fresh cattle manure; CCM: composted cattle manure; NUE: Apparent N use efficiency; FNE: fertilizer N equivalency; PMS$_1$: paper mill sludges with C/N <15; PMS$_2$, paper mill sludges with C/N of 20.

Data obtained in this study generally show that FCM and CCM gave lower NUE compared to mineral N fertilizer that is readily soluble as has also been observed by Sommer [33] and Gutser *et al.* [34]. Based on the total NUE obtained in the first and residual years, N recovered by the potato crop from applied PMS in fall or spring varied from 27% to 29%, which represented 62 to 82 kg N ha^{-1}. Nitrogen recovered from FCM and CCM was much lower than that of PMS. Our results evidence that it is efficient to supplement N fertilizer to organic amendments to meet crop N needs and to maintain a high marketable potato yield.

3.4. Incidence of Common Scab and Black Scurf

The levels of common scab ranged from 0.25% to 2% in 2004 and from 22.0% to 33.8 % in 2005 (Figure 4A,B). The analysis of variance showed that organic amendment application in 2004 had no significant effect on common scab incidence ($P = 0.1348$) in the first year of application (Table 2). In contrast, common scab incidence was significantly increased by mineral N fertilizer application in 2004 (Table 2). In 2005, the effect of organic amendment and mineral fertilizer on common scab incidence was not significant. As for common scab, organic amendments application had no effect on black scurf levels in 2004, but the mineral N fertilization effect was significant (Table 2). In 2005, symptoms of black scurf were lower than in 2004 (Figure 4C *versus* Figure 4D) and opposite trends were observed with common scab, where the scab incidence was higher in 2005 than in 2004. Scab disease severity is impacted by several factors such as soil type and organic amendments, crop rotation, soil moisture and soil acidity. Soil moisture levels close to field capacity in the weeks following tuberization inhibit scab infection (Lapwood and Hering [35]; Lapwood *et al.* [36]). Black scurf is also controlled by environmental conditions. Shoot development is fast when the planting is done into warmer soils and is unlikely to be affected by black scurf. The difference observed between the two years on common scab and on black scurf is probably related to different environmental conditions in both years. The year 2005 seemed to be warmer than 2004 (Figure 1B) which may have inhibited black scurf incidence, and 2004 seemed to be moister during tuber formation than 2005 and these conditions may have decreased scab incidence.

Results of this study showed that organic amendments did not increase scab and black scurf incidence compared to mineral N fertilizer. In a study on corn, N'Dayegamiye [1] demonstrated that paper mill sludges and dairy cattle manure significantly increased soil microbial and enzymatic activity. Organic amendments probably increased soil microbial population and activity and reduced potato diseases by competition as was hypothesized by Darby *et al.* [19].

Figure 4. Effects of mineral N fertilization and organic amendments with or without supplemental N fertilizer (N) on common scab (**A**, **B**) and black scurf (**C**, **D**) in 2004 and 2005.
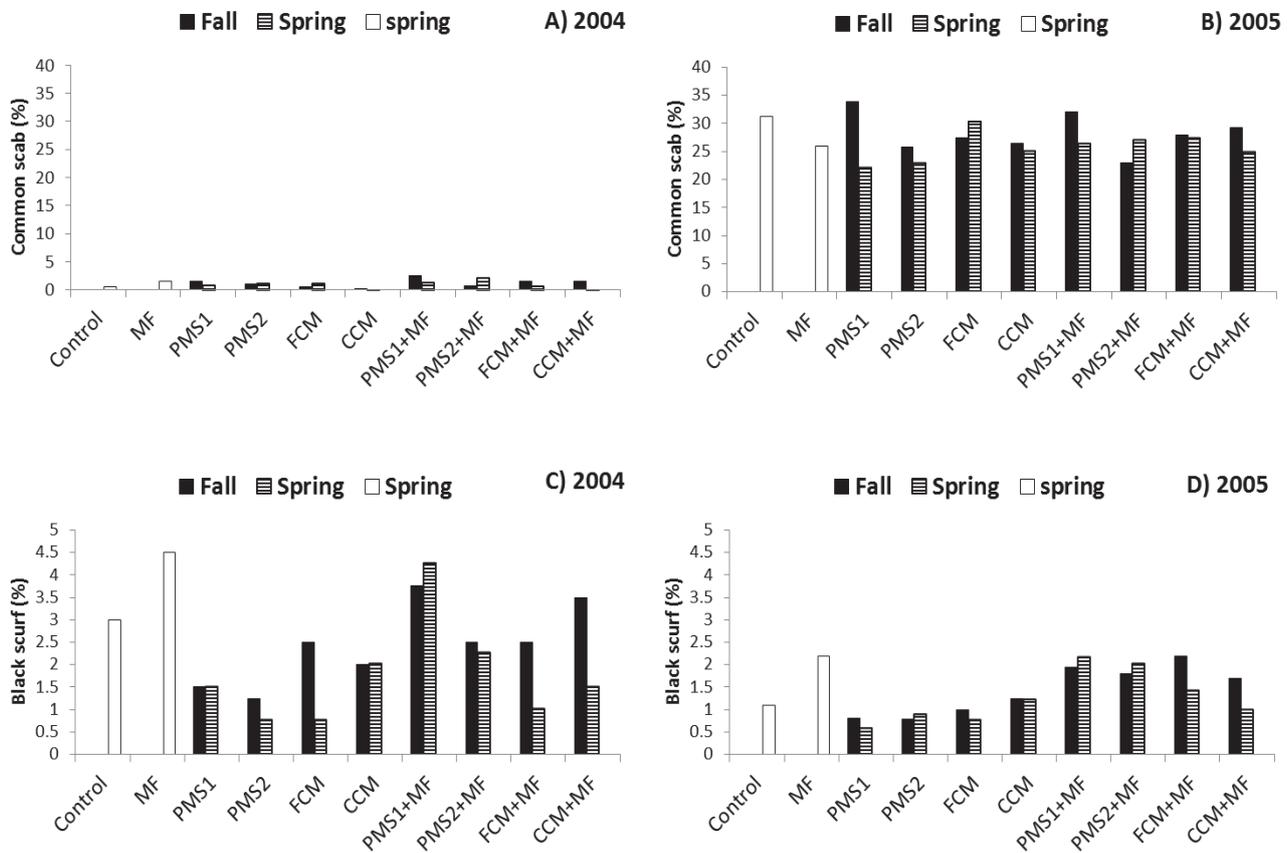
Control: non N fertilizer was applied; MF: mineral fertilizer applied at 150 kg N ha^{-1}; PMS$_1$: paper mill sludge with C/N <15; PMS$_2$: mixed paper mill sludge with C/N of 20; FCM: fresh dairy cattle manure; CCM: composted dairy cattle manure; PMS$_1$ + FM, PMS$_2$ + MF, FCM + MF, CCM + MF refer to PMS$_1$, PMS$_2$, FCM, and CCM supplemented with mineral fertilizer at a rate of 90 kg N ha^{-1}.

4. Conclusions

The application of solid dairy cattle manures and paper mill sludges increased marketable potato yield by 2.5 to 16.4 Mg ha^{-1}, compared to the unamended and unfertilized soil. The highest potato yield and N uptake were obtained where organic amendments were supplemented with mineral N fertilizer (90 kg N ha^{-1}). In 2004 and 2005, the NUE and FNE were higher with PMS than FCM and CCM. Based on the total NUE obtained in the first and residual years, N recovered by the potato crop from applied PMS in fall or spring varied from 27% to 29%, which corresponded to 62 to 82 kg N ha^{-1}. Potato yield and N uptake were increased when organic amendments were supplied with mineral N fertilizer at 90 kg N ha^{-1}. This suggests that supplemental N fertilizer is necessary even for organic amendments with high available N to meet potato N needs and to increase marketable yield. The application of organic amendments did not increase potato common scab and black scurf incidences compared with mineral N fertilizer treatment. This study shows that appropriate organic amendment management can increase potato yield and quality and reduce N fertilizer requirement.

Acknowledgments

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