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Short-term residual effects of various amendments on organic C and N, and available nutrients in soil under organic crop production

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ABSTRACT

Two 3-year (2008-2010, wheat-pea-barley) field experiments were conducted on certified organic farms near Spalding (Dark Brown Chernozem-Typic Haploboroll) and Star City (Gray Luvisol-Typic Haplocryalf) in northeastern Saskatchewan, Canada, to determine the residual effects of compost, alfalfa pellets, wood ash, rock phosphate, *Penicillium bilaiae*, gypsum and MykePro on organic C and N (total organic C [TOC], total organic N [TON], light fraction organic C [LFOC], light fraction organic N [LFON]) and mineralizable N (N_{min}) in the 0 - 15 cm soil layer, and ammonium-N, nitrate-N, extractable P, exchangeable K and sulphate-S in the 0 - 15, 15 - 30 and 30 - 60 cm soil layers in autumn 2010. Compared to the unamended control, mass of TOC, TON, LFOC and LFON increased with compost and alfalfa pellets in both soils. However, the increases were much more pronounced for LFOC (by 125% - 133%) or LFON (by 102% - 103%) than TOC (by 19% - 29%) or TON (by 25% - 40%). The N_{min} also increased in these two treatments compared to the control, but the increases were much smaller for compost than alfalfa pellets. In general, residual nitrate-N increased with increasing rate of compost and alfalfa pellets in the 0 - 15 and 15 - 30 cm layers in both soils. Extractable P increased with compost and exchangeable K with alfalfa pellets, but only in the 0 - 15 cm soil layer. Sulphate-S increased with compost, but mainly in the 30 - 60 cm soil layer. Soil pH usually increased with compost and more so with wood ash, but no effect of any amendment on ammonium-N. Overall, the quantity of organic C and N, and available nutrients in soil increased with compost and/or alfalfa pellets, but the magnitude varied with amendment and/or soil type. In conclusion, our findings suggest that soil quality and fertility can be improved with these organic amendments, suggesting sustainability of production from organic crops.

Keywords: Amendments; Compost; Organic C and N; pH; Soil Fertility; Soil Quality

1. INTRODUCTION

In organic farming, synthetic fertilizers/chemicals cannot be applied to prevent nutrient deficiencies, so compost manure, industrial processing byproducts (e.g., wood ash), microbial inoculants (e.g., *Penicillium bilaiae*, MykePro, JumStart) and other amendments (e.g., alfalfa pellets, rock phosphate, gypsum) are used as organic fertilizers to increase production of organic crops. Fertilization with organic amendments, such as compost manure/farm yard manure (FYM), alfalfa pellets/powder, distiller grain and thin stillage can have both direct (e.g., enhancing organic C in soil) and indirect (e.g., providing available nutrients after decomposition/mineralization) benefits on soil physical, chemical and biological properties, and crop yields [1-9]. Inorganic amendments and microbial inoculants, such as wood ash, rock phosphate, *Penicillium bilaiae*, MykePro, gypsum and elemental S, have been investigated for their potential as organic fertilizers in many studies, but their effectiveness to increase the availability of P or S in soil, and subsequently improve crop yield varies with nutrient source/type, severity of P, S and other nutrients deficiency in soil, soil type and climatic conditions [10-13].

Soil quality is linked to organic matter (or organic C) in soil, and the increase of organic C in soil is a function of the amount of C input to soil and its balance with decomposition [14-16]. Thus, organic amendments (because of both direct and indirect C input) can have much greater residual benefits in improving soil organic matter/quality and fertility compared to inorganic amendments which contribute only indirectly to C input in soil

[3-6,17-19]. However, the effects of various amendments on soil properties vary with soil-climatic conditions.

The perception is that organic farming practices, because of zero input of chemical N fertilizers, can reduce accumulation and leaching of nitrate-N in the soil profile. However, Kirchmann and Bergstrom [20] could not find evidence of any research in their review paper. In contrast, other researchers [21-23] claimed that the continuous use of organic manures alone may result in asychronicity between the N supply and the N demand by crops, which may lead to a greater potential of nitrate leaching, especially under wet/humid climatic conditions. The information on the residual effects of organic and inorganic amendments or microbial inoculants on soil properties is lacking under Canadian Prairie soil-climatic conditions, especially in the Parkland region. The objective of this study was to determine the residual effects of various amendments (compost, alfalfa pellets, wood ash, rock phosphate, *Penicillium bilaiae*, gypsum and MykePro) in autumn 2010 after three annual applications (2008—wheat, 2009—pea, and 2010—barley) on organic C and N (total organic C [TOC], total organic N [TON], light fraction organic C [LFOC], light fraction organic N [LFON]), mineralizable N (N_{min}) and pH in 0 - 15 cm soil, and ammonium-N, nitrate-N, extractable P, exchangeable K and sulphate-S in the 0 - 15, 15 - 30 and 30 - 60 cm soil layers in two field experiments on certified organic farms in northeastern Saskatchewan, Canada.

2. MATERIALS AND METHODS

Two 3-year (2008-2010) field experiments were established on certified organic farms in spring 2008 near Spalding (Dark Brown Chernozem-Typic Haploboroll) and Star City (Gray Luvisol-Typic Haplocryalf) in northeastern Saskatchewan, Canada. During the summer of 2007, the land was managed as tilled fallow in Experiment 1 at Spalding, and as green manure fallow in Experiment 2 at Star City. For this area, the long-term average precipitation in the growing season (May, June, July and August) is about 250 mm and air temperatures in May to August range from about 9˚C to 20˚C. At the experimental sites, the precipitation in the 2008 growing season was below average, with little precipitation in May. In 2009, the growing season precipitation was near long-term average, with slightly lower than average precipitation in May and slightly higher than average precipitation in August. In 2010, the growing season precipitation was much higher than average (especially in June, and also in April prior to spring), and relatively cooler air temperatures in most summer. A randomized complete block design was used to lay out the treatments in four replications. Each plot was 7.5 m long and 1.8 m wide.

In Experiment 1, there were 23 treatments: 1) Control (no amendment), 2) Compost @ 10 $Mg \cdot ha^{-1}$, 3) Compost @ 20 $Mg \cdot ha^{-1}$, 4) Compost @ 30 $Mg \cdot ha^{-1}$, 5) Wood ash @ 1 $Mg \cdot ha^{-1}$, 6) Wood ash @ 2 $Mg \cdot ha^{-1}$, 7) Wood ash @ 3 $Mg \cdot ha^{-1}$, 8) Rock phosphate granular @ 10 $kg \cdot P \cdot ha^{-1}$, 9) Rock phosphate granular @ 20 $kg \cdot P \cdot ha^{-1}$, 10) Rock phosphate granular @ 30 $kg \cdot P \cdot ha^{-1}$, 11) Rock phosphate finely-ground @ 10 $kg \cdot P \cdot ha^{-1}$, 12) Rock phosphate finely-ground @ 20 $kg \cdot P \cdot ha^{-1}$, 13) Rock phosphate finely-ground @ 30 $kg \cdot P \cdot ha^{-1}$, 14) Alfalfa pellets @ 1 $Mg\ ha^{-1}$, 15) Alfalfa pellets @ 2 $Mg \cdot ha^{-1}$, 16) Alfalfa pellets @ 4 $Mg \cdot ha^{-1}$, 17) Alfalfa pellets @ 6 $Mg \cdot ha^{-1}$, 18) Control + inoculate seed with *Penicillium bilaiae*, 19) Rock phosphate granular @ 20 $kg \cdot P \cdot ha^{-1}$ + inoculate seed with *Penicillium bilaiae*, 20) Rock phosphate finely-ground @ 20 $kg \cdot P \cdot ha^{-1}$ + inoculate seed with *Penicillium bilaiae*, 21) Pulse (no amendment), 22) Cereal + pulse intercrop (no amendment), and 23) MykePro.

In Experiment 2, there were 21 treatments: 1) Control (no amendment), 2) Compost @ 10 $Mg \cdot ha^{-1}$, 3) Compost @ 20 $Mg \cdot ha^{-1}$, 4) Compost @ 30 $Mg \cdot ha^{-1}$, 5) Wood ash @ 1 $Mg \cdot ha^{-1}$, 6) Wood ash @ 2 $Mg \cdot ha^{-1}$, 7) Wood ash @ 3 $Mg \cdot ha^{-1}$, 8) Alfalfa pellets @ 1 $Mg \cdot ha^{-1}$, 9) Alfalfa pellets @ 2 $Mg \cdot ha^{-1}$, 10) Alfalfa pellets @ 4 $Mg \cdot ha^{-1}$, 11) Alfalfa pellets @ 6 $Mg \cdot ha^{-1}$, 12) Gypsum @ 10 $kg \cdot S \cdot ha^{-1}$, 13) Gypsum @ 20 $kg \cdot S \cdot ha^{-1}$, 14) Pulse (no amendment), 15) Cereal + pulse intercrop (no amendment), 16) Control + inoculate seed with *Penicillium bilaiae*, 17) Rock phosphate finely-ground @ 20 $kg \cdot P \cdot ha^{-1}$, 18) Rock phosphate finely-ground @ 20 $kg \cdot P \cdot ha^{-1}$ + inoculate seed with *Penicillium bilaiae*, 19) Rock phosphate granular @ 20 $kg \cdot P \cdot ha^{-1}$, 20) Rock phosphate granular @ 20 $kg \cdot P \cdot ha^{-1}$ + inoculate seed with *Penicillium bilaiae*, and 21) MykePro.

Amendments were broadcast on soil surface and all plots were rotovated to a depth of about 8 cm few days prior to seeding. In both experiments, plots were seeded to wheat in 2008, pea in 2009 and barley in 2010, using a double-disc press drill at 17.8 cm row spacing. In each plot, the crop at maturity was harvested with a plot combine to determine seed yield, and the chopped straw was returned/retained in each plot. In autumn 2010, soil samples were taken in selected treatments in Experiments 1 and 2 for determinations of TOC, TON, LFOC, LFON and pH in the 0 - 15 cm depth, and ammonium-N, nitrate-N, extractable P, exchangeable K and sulphate-S in the 0 - 15, 15 - 30 and 30 - 60 cm depths.

For TOC, TON, LFOC, LFON and pH, soil cores at 10 locations in each plot were collected using a 2.4 cm diameter coring tube. Bulk density of soil was determined by the core method using soil weight and core volume [24]. The soil samples were air dried at room temperature after removing coarse roots and easily detectable crop residues, and ground to pass a 2-mm sieve.

Sub-samples were pulverized in a vibrating-ball mill (Retsch, Type MM2, Brinkman Instruments Co., Toronto, Ontario) for determination of TOC, TON, LFOC and LFON in soil. Soil samples used for organic C and N analyses were tested for the presence of inorganic C (carbonates) using dilute HCl, and none was detected in any soil sample. Therefore, C in soil associated with each fraction was considered to be of organic origin. Total organic C in soil was measured by Dumas combustion using a Carlo Erba instrument (Model NA 1500, Carlo Erba Strumentazione, Italy), and Technicon Industrial Systems [25] method was used to determine TON in the soil. Light fraction organic matter (LFOM) was separated using a NaI solution of 1.7 $Mg \cdot m^{-3}$ specific gravity, as described by Janzen *et al.* [26] and modified by Izaurralde *et al.* [27]. The C and N in LFOM (LFOC, LFON) were measured by Dumas combustion. The amounts of mineralizable N in the 0 - 15 cm layer were estimated from the quantities of ammonium-N + nitrate-N mineralized from soil (after using soil bulk density) during a 10 day incubation at 25˚C and a soil water potential of $-30\ J \cdot kg^{-1}$ [28].

Soil samples (ground to pass a 2-mm sieve) taken for organic C and N from the 0 - 15 cm layer were also monitored for pH in 0.01 M $CaCl_2$ solution with a pH meter. For other chemical properties, soil cores (using a 4 cm diameter coring tube) were collected at 4 locations in each plot from the 0 - 15, 15 - 30 and 30 - 60 cm layers. The bulk density of each depth was calculated using soil weight and core volume [24]. The soil samples were air dried at room temperature, ground to pass a 2-mm sieve, and analyzed for ammonium-N [29] and nitrate-N [30] by extracting soil in a 1:5 soil: 2 M KCl solution, extractable P [25] by extracting soil in Kelowna extract, exchangeable K [31]and sulphate-S [32].

The data on each parameter were subjected to analyses of variance (ANOVA) using GLM procedure in SAS [33]. For each ANOVA, the least significant difference at $P \leq 0.05$ ($LSD_{0.05}$) was used to determine significant differences between treatment means, and standard error of the mean (SEM) and significance are reported.

3. RESULTS

3.1. Soil Organic C and N

Mass of TOC and TON in the 0 - 15 cm soil increased significantly after three annual applications of compost at both sites compared to the unamended control (**Tables 1** and **2**). Mass of TOC and TON also increased with alfalfa pellets, but the increases were not significant. There was no effect of other amendments on TOC or TON in soil. The relative increases in C or N were 27.5% for TOC and 24.8% for TON for compost at Spalding. The corresponding values with compost at Star City were 32.4% and 24.5% for TOC and TON, respectively.

Compared to the control, mass of LFOC and LFON in soil increased considerably with compost and moderately with alfalfa pellets at both sites. However, there was no significant effect of other amendments treatment on LFOC or LFON in soil. At Spalding, the relative increases were 133% for LFOC and 103% for LFON from compost and 19% for LFOC and 25% for LFON from

Table 1. Mass of total organic C (TOC), total organic N (TON), light fraction organic C (LFOC) and light fraction organic N (LFON) in the 0 - 15 cm soil layer in autumn 2010 after three annual applications of various amendments at Spalding, Saskatchewan (Experiment 1).

Treatment		TOC or TON ($Mg \cdot C$ or $N \cdot ha^{-1}$)		LFOC or LFON ($kg \cdot C$ or $N \cdot ha^{-1}$)		N_{min} ($kg \cdot N \cdot ha^{-1}$)
#	Amendments	TOC	TON	LFOC	LFON	
1	Control (no amendment)	38.20	2.981	2185	111.8	72.5
3	Compost @ 20 $Mg \cdot ha^{-1}$	48.71	3.720	5100	230.5	75.3
6	Wood ash @ 2 $Mg \cdot ha^{-1}$	37.96	2.960	2583	133.7	
9	Rock phosphate granular @ 20 $kg \cdot P \cdot ha^{-1}$	38.79	2.876	2499	126.4	
12	Rock phosphate fine @ 20 $kg \cdot P \cdot ha^{-1}$	39.32	3.043	2421	118.5	
16	Alfalfa pellets @ 4 $Mg \cdot ha^{-1}$	41.81	3.274	2604	139.6	86.5
18	Control + *Penicillium bilaiae*	39.83	2.991	2177	109.3	
23	MykePro	38.41	2.919	2473	122.7	
	$LSD_{0.05}$	4.14	0.284	939	44.7	ns
	SEM	1.402^{***}	0.0962^{***}	319.4^{***}	15.19^{***}	6.39^{ns}

***and ns refer to significant treatment effects in ANOVA at $P \leq 0.001$ and not significant, respectively.

Table 2. Mass of total organic C (TOC), total organic N (TON), light fraction organic C (LFOC) and light fraction organic N (LFON) in the 0 - 15 cm soil layer in autumn 2010 after three annual applications of various amendments at Star City, Saskatchewan (Experiment 2).

Treatment		TOC or TON (Mg·C or N·ha^{-1})		LFOC or LFON (kg·C or N·ha^{-1})		N_{min} (kg·N·ha^{-1})
#	Amendments	TOC	TON	LFOC	LFON	
1	Control (no amendment)	33.79	3.012	3379	175.0	67.1
3	Compost @ 20 Mg·ha^{-1}	44.75	3.749	7586	353.5	78.9
6	Wood ash @ 2 Mg·ha^{-1}	32.60	2.836	3113	163.0	
10	Alfalfa pellets @ 4 Mg·ha^{-1}	35.81	3.198	4353	244.2	87.9
13	Gypsum @ 20 kg·S·ha^{-1}	34.72	2.938	3528	189.5	
16	Control + *Penicillium bilaiae*	32.83	2.884	3332	173.7	
17	Rock phosphate fine @ 20 kg·P·ha^{-1}	34.54	3.012	3735	194.6	
19	Rock phosphate granular @ 20 kg·P·ha^{-1}	33.90	3.013	3547	188.6	
21	MykePro	34.30	3.048	3575	190.7	
	$LSD_{0.05}$	3.20	0.290	730	33.5	14.8
	SEM	1.096***	0.0099***	250.2***	11.46***	4.29*

* and *** refer to significant treatment effects in ANOVA at $P \leq 0.05$ and $P \leq 0.001$, respectively.

alfalfa pellets. The corresponding values at Star City were 125% for LFOC and 102% for LFON from compost and 29% for LFOC and 40% for LFON from alfalfa pellets. This suggests that relative increases in C or N were greater for LFOC or LFON than TOC or TON. Mass of N_{min} was significantly greater (but small) with compost, but N_{min} increased substantially with alfalfa pellets compared to the control.

3.2. Soil pH and Residual Available N, P, K and S in the Soil Profile

In the soil samples taken to the 15 cm depth, there was a significant effect of treatments on pH, nitrate-N, extractable P, exchangeable K and sulphate-S in both soils, but the magnitude varied with amendment and soil chemical property (**Tables 3** and **4**). There was a signifycant increase in soil pH with wood ash at Spalding, and with wood ash and compost at Star City. Practically, there was little or no effect of any amendment on the amount of ammonium-N in soil, although the overall treatment effect was significant (but small) at Star City. The amount of residual nitrate-N in soil mainly increased with compost at Spalding and with alfalfa pellets at Star City. Extractable P increased substantially with compost in both soils, moderately at Star city and slightly at Spalding with wood ash, and tended to increase with other amendments at Star City. Exchangeable K in soil increased considerably with compost, which was followed closely by wood ash and alfalfa pellets at both sites. Sulphate-S in soil increased with wood ash, and more so with compost and/or gypsum at both sites.

In the soil profile samples taken to the 60 cm depth, there was a significant overall effect of treatments on the residual amounts of nitrate-N, extractable P, exchangeable K and sulphate-S in both soils, but the magnitude of change varied with amendment in different soil depth layers (**Tables 5-8**). Residual nitrate-N increased with increasing rate of alfalfa pellets and compost in both soils, mainly in the 0 - 15 and 15 - 30 cm layers. Extractable P increased substantially with increasing rate of compost in both soils, but only in the 0 - 15 cm layer. Exchangeable K increased considerably with increasing rate of alfalfa pellets only in the 0 - 15 cm layer in both soils. Sulphate-S increased with increasing rate of compost in both soils, but mainly in the 30 - 60 cm layer. There was no effect of any amendments on ammonium-N in both soils (data not shown).

4. DISCUSSION

4.1. Soil Organic C and N

Previous research in the Canadian Prairies has shown positive effects on crop yield and soil quality from manure application, and manure was found to be the best amendment to restore deteriorated/eroded soils containing low organic matter and poor crop yields [27,34-38]. Similarly, the highest increase in TOC and TON from compost than other amendments in our study was due to its dual effect by directly contributing to organic C and N, plus additional indirect contribution of C from increased

Table 3. Soil pH, and amount of ammonium-N, nitrate-N, extractable P, exchangeable K and sulphate-S in 0 - 15 cm soil layer in autumn 2010 after three annual applications of various amendments at Spalding, Saskatchewan (Experiment 1).

Treatment		pH	Ammonium-N ($kg \cdot N \cdot ha^{-1}$)	Nitrate-N ($kg \cdot N \cdot ha^{-1}$)	Extract. P ($kg \cdot P \cdot ha^{-1}$)	Exch. K ($kg \cdot K \cdot ha^{-1}$)	Sulphate-S ($kg \cdot S \cdot ha^{-1}$)
#	Amendments						
1	Control (no amendment)	7.1	3.8	6.6	15.3	395	2.3
3	Compost @ 20 $Mg \cdot ha^{-1}$	7.3	3.4	11.1	103.4	689	5.0
6	Wood ash @ 2 $Mg \cdot ha^{-1}$	7.7	2.6	6.1	19.8	579	3.8
9	Rock phosphate granular @ 20 $kg \cdot P \cdot ha^{-1}$	7.5	3.5	7.5	15.4	340	2.5
12	Rock phosphate fine @ 20 $kg \cdot P \cdot ha^{-1}$	7.4	5.0	7.6	12.2	343	2.8
16	Alfalfa pellets @ 4 $Mg \cdot ha^{-1}$	7.4	4.2	8.2	12.7	471	2.2
18	Control + *Penicillium bilaiae*	7.3	3.4	7.6	14.5	320	2.5
23	MykePro	7.1	3.5	8.3	14.6	349	2.6
	$LSD_{0.05}$	0.4	ns	1.7	13.4	91	0.6
	SEM	0.12^{*}	0.60^{ns}	0.57^{***}	4.57^{***}	31.1^{***}	0.22^{***}

*, *** and ns refer to significant treatment effects in ANOVA at P ≤ 0.05, P ≤ 0.001 and not significant, respectively.

Table 4. Soil pH, and amount of ammonium-N, nitrate-N, extractable P, exchangeable K and sulphate-S in 0 - 15 cm soil layer in autumn 2010 after three annual applications of various amendments at Star City, Saskatchewan (Experiment 2).

Treatment		pH	Ammonium-N	Nitrate-N	Extract. P	Exch. K	Sulphate-S
#	Amendments						
1	Control (no amendment)	6.2	4.5	13.2	15.4	382	2.4
3	Compost @ 20 $Mg \cdot ha^{-1}$	7.1	3.9	13.8	149.6	818	5.8
6	Wood ash @ 2 $Mg \cdot ha^{-1}$	7.6	2.5	10.8	32.9	584	4.5
10	Alfalfa pellets @ 4 $Mg \cdot ha^{-1}$	6.4	4.4	16.4	18.4	594	3.0
13	Gypsum @ 20 $kg \cdot S \cdot ha^{-1}$	6.3	5.2	12.8	17.9	411	5.6
16	Control + *Penicillium bilaiae*	6.3	4.6	11.0	17.6	392	2.7
17	Rock phosphate fine @ 20 $kg \cdot P \cdot ha^{-1}$	6.2	4.6	11.2	20.1	377	2.6
19	Rock phosphate granular @ 20 $kg \cdot P \cdot ha^{-1}$	6.2	3.6	10.8	20.2	404	2.7
21	MykePro	6.2	4.3	11.8	22.5	392	2.5
	$LSD_{0.05}$	0.2	0.8	2.4	13.1	63	1.1
	SEM	0.08^{***}	0.27^{***}	0.82^{***}	4.49^{***}	21.7^{***}	0.36^{***}

***refers to significant treatment effect in ANOVA at P ≤ 0.001.

crop residue (roots, stubble, straw, chaff/fallen leaves) returned to the land/soil, as evidenced by greatest increase in straw yield in this treatment [39]. Inorganic amendments usually supply specific nutrients and do not contribute directly to soil organic matter, resulting in much less contribution to soil organic C and N. Other recent research in Germany has also shown significant increase in soil organic matter after four annual applications of farm yard manure (FYM) to organic crops [7].

The relative greater increases in C or N for LFOC or LFON than TOC or TON in our study are in agreement with other research, where light organic fraction was also more responsive to management practices than total organic fraction [14-16]. The greater build-up of light organic fraction at Star City than Spalding was probably due to the differences in soil type (Gray Luvisol soil at Star City versus Dark brown Chernozem at Spalding) and climatic conditions (relatively warmer temperature at Spalding than Star City) at the two sites.

In spite of greater mass of LFON in compost than alfalfa pellets treatment in our study, mass of N_{min} was much greater in alfalfa pellets than compost treatment. It

Table 5. Amount of nitrate-N in soil in autumn 2010 after three annual applications of various amendments at Spalding (Experiment 1) and Star City (Experiment 2), Saskatchewan.

Treatment		Nitrate-N ($kg·N·ha^{-1}$) in soil layers (cm) at Spalding					Nitrate-N ($kg·N·ha^{-1}$) in soil layers (cm) at Star City			
Amendments		0 - 15	15 - 30	30 - 60	0 - 60		0 - 15	15 - 30	30 - 60	0 - 60
Control (no amendment)	1	5.7	2.5	4.9	13.1	1	13.7	4.9	5.7	24.3
Compost @ 10 $Mg·ha^{-1}$	2	5.6	3.1	4.9	13.6	2	11.3	4.7	5.4	21.4
Compost @ 20 $Mg·ha^{-1}$	3	8.8	4.9	6.0	19.7	3	12.5	4.9	5.4	22.8
Compost @ 30 $Mg·ha^{-1}$	4	9.9	6.8	7.6	24.3	4	15.4	6.9	5.7	28.0
Alfalfa pellets @ 1 $Mg·ha^{-1}$	14	6.7	2.9	5.3	14.9	8	9.8	7.0	5.6	22.4
Alfalfa pellets @ 2 $Mg·ha^{-1}$	15	4.5	2.2	3.6	10.3	9	11.2	4.9	6.3	22.4
Alfalfa pellets @ 4 $Mg·ha^{-1}$	16	7.5	3.9	5.5	16.9	10	16.2	6.2	5.7	28.1
Alfalfa pellets @ 6 $Mg·ha^{-1}$	17	8.4	5.1	6.5	20.0	11	17.2	7.0	9.7	33.9
$LSD_{0.05}$		2.8	2.4	1.9	6.0		ns	2.3	3.1	8.2
SEM		0.96^{*}	0.81^{**}	0.66^{*}	2.04^{**}		2.08^{ns}	$0.80^{\bullet}$	$1.04^{\bullet}$	$2.78^{\bullet}$

$^{\bullet}$, *, ** and ns refer to significant treatment effects in ANOVA at $P \le 0.1$, $P \le 0.05$, $P \le 0.01$ and not significant, respectively.

Table 6. Amount of extractable P in soil in autumn 2010 after three annual applications of various amendments at Spalding (Experiment 1) and Star City (Experiment 2), Saskatchewan.

Treatment		Extractable P ($kg·P·ha^{-1}$) in soil layers (cm) at Spalding					Extractable P ($kg·P·ha^{-1}$) in soil layers (cm) at Star City			
Amendments		0 - 15	15 - 30	30 - 60	0 - 60		0 - 15	15 - 30	30 - 60	0 - 60
Control (no amendment)	1	15.4	7.5	13.2	36.1	1	16.4	9.4	13.8	36.8
Compost @ 10 $Mg·ha^{-1}$	2	50.1	5.3	11.5	66.9	2	59.3	8.8	13.6	81.7
Compost @ 20 $Mg·ha^{-1}$	3	80.7	5.4	13.1	99.2	3	91.3	11.8	9.7	112.8
Compost @ 30 $Mg·ha^{-1}$	4	114.1	12.4	18.8	145.3	4	179.0	12.6	17.0	208.6
Alfalfa pellets @ 1 $Mg·ha^{-1}$	14	9.6	4.4	11.2	25.2	8	15.2	13.4	7.9	36.5
Alfalfa pellets @ 2 $Mg·ha^{-1}$	15	8.1	2.1	8.8	19.0	9	17.4	10.6	14.3	42.3
Alfalfa pellets @ 4 $Mg·ha^{-1}$	16	10.9	3.7	8.8	23.4	10	18.4	10.2	11.9	40.5
Alfalfa pellets @ 6 $Mg·ha^{-1}$	17	11.2	3.0	10.0	24.2	11	20.7	8.4	9.7	38.8
$LSD_{0.05}$		37.9	ns	ns	43.7		30.2	ns	ns	30.7
SEM		12.89^{***}	2.79^{ns}	3.00^{ns}	14.86^{***}		10.3^{***}	2.27^{ns}	2.71^{ns}	10.44^{***}

***and ns refer to significant treatment effects in ANOVA at $P \le 0.001$ and not significant, respectively.

is possible that alfalfa pellets may have higher concentration of total and labile organic N (and narrow C:N ratio) than compost, resulting in greater N_{min}. The greater amount of N_{min} in soil suggests that N-supplying power/capacity of soil can be improved with organic amendments, but this may also increase the potential for greenhouse gas (GHG) emissions if large amounts of N are mineralized to nitrate-N during off-growing season. Similarly, application of organic manure in a study in China increased net ammonification, net nitrification or net N mineralization rate in soil compared to control. In a growth chamber study, Qian *et al.* [8] showed significant increase in total N in soil with application of alfalfa powder and anticipated increase in N availability to subsequent crops. In a field study in Germany, Heitkamp *et al.* [7] found significant increase in labile N with application of FYM for four years, and the increase was strongly related to rate of FYM and also to crop yield. In another study in southern Alberta, Canada, long-term applications of cattle manure increased potentially mineralizable N and P in soil samples collected every five years over 25-year period [40]. Because availability of

Table 7. Amount of extractable K in soil in autumn 2010 after three annual applications of various amendments at Spalding (Experiment 1) and Star City (Experiment 2), Saskatchewan.

Treatment		Extractable K (kg·K·ha^{-1}) in soil layers (cm) at Spalding					Extractable K (kg·K·ha^{-1}) in soil layers (cm) at Star City			
Amendments		0 - 15	15 - 30	30 - 60	0 - 60		0 - 15	15 - 30	30 - 60	0 - 60
Control (no amendment)	1	349	344	521	1214	1	313	290	582	1185
Compost @ 10 Mg·ha^{-1}	2	539	328	473	1340	2	498	311	607	1416
Compost @ 20 Mg·ha^{-1}	3	649	304	448	1401	3	626	313	679	1618
Compost @ 30 Mg·ha^{-1}	4	834	335	465	1634	4	935	352	625	1912
Alfalfa pellets @ 1 Mg·ha^{-1}	14	330	334	437	1101	8	336	343	623	1302
Alfalfa pellets @ 2 Mg·ha^{-1}	15	339	309	426	1074	9	386	339	599	1324
Alfalfa pellets @ 4 Mg·ha^{-1}	16	409	312	460	1181	10	442	364	602	1408
Alfalfa pellets @ 6 Mg·ha^{-1}	17	521	270	424	1215	11	491	338	609	1438
$LSD_{0.05}$		221	ns	ns	333		175	ns	ns	279
SEM		75.1^{***}	18.2^{ns}	36.8^{ns}	113.1^{*}		59.5^{***}	22.6^{ns}	49.0^{ns}	95.0^{**}

*, **, ***and ns refer to significant treatment effects in ANOVA at P ≤ 0.05, P ≤ 0.01, P ≤ 0.001 and not significant, respectively.

Table 8. Amount of sulphate-S in soil in autumn 2010 after three annual applications of various amendments at Spalding (Experiment 1) and Star City (Experiment 2), Saskatchewan.

Treatment		Sulphate-S (kg·S·ha^{-1}) in soil layers (cm) at Spalding					Sulphate-S (kg·S·ha^{-1}) in soil layers (cm) at Star City			
Amendments		0 - 15	15 - 30	30 - 60	0 - 60		0 - 15	15 - 30	30 - 60	0 - 60
Control (no amendment)	1	3.1	2.8	5.5	11.4	1	3.3	3.1	7.2	13.6
Compost @ 10 Mg·ha^{-1}	2	5.1	3.7	21.4	30.2	2	4.7	3.5	16.0	24.2
Compost @ 20 Mg·ha^{-1}	3	4.3	3.7	16.6	24.6	3	4.7	8.2	26.2	39.1
Compost @ 30 Mg·ha^{-1}	4	6.1	7.7	67.9	81.7	4	6.5	6.2	49.2	61.9
Alfalfa pellets @ 1 Mg·ha^{-1}	14	2.6	2.4	5.3	10.3	8	2.8	3.4	7.2	13.4
Alfalfa pellets @ 2 Mg·ha^{-1}	15	2.6	2.6	4.8	11.0	9	2.8	2.5	5.7	11.0
Alfalfa pellets @ 4 Mg·ha^{-1}	16	2.9	2.6	6.4	11.9	10	3.3	2.9	6.0	12.2
Alfalfa pellets @ 6 Mg·ha^{-1}	17	2.3	2.3	5.6	10.1	11	3.4	2.8	6.5	12.7
$LSD_{0.05}$		1.7	1.9	33.1	34.9		1.3	3.8	13.0	12.4
SEM		0.56^{***}	0.64^{***}	11.25^{**}	11.86^{**}		0.43^{***}	1.31^{*}	4.42^{***}	4.23^{***}

*, ** and ***refer to significant treatment effects in ANOVA at P ≤ 0.05, P ≤ 0.01 and P ≤ 0.001, respectively.

soil N is usually the most limiting factor for crop production [41], available N produced by mineralization of native soil organic N (*i.e.*, N_{min}) should be considered for determination of N requirements of crops [42].

4.2. Soil pH and Residual Available N, P, K and S in the Soil Profile

The increase in soil pH with wood ash and/or compost was most likely due to the alkaline/basic nature of these amendments, especially wood ash. Wood ash contained very high concentration of Ca (up to 28.4 g Ca·kg^{-1}), followed by moderate Ca concentration in alfalfa pellets (3.5 g Ca·kg^{-1}), plus high concentrations of other cations. Other research has also shown wood ash to be an excellent substitute to lime for increasing soil pH and better amendment for crop production on acidic soils apparently because of the presence of other plant nutrients in wood ash compared to only Ca and Mg in lime [43].

There was no build-up of residual ammonium-N in soil even after three annual applications of organic amendments, and this was probably because of the rapid nitrification of any ammonium-N released during mineralization of organic matter. The amount of residual nitrate-N in soil increased with increasing rate of compost and/or alfalfa pellets in the 0 - 60 cm soil profile, but the increase was small. This suggests little potential risk of nitrate leaching below the root zone in our study sites. This could be due to shorter duration of our study (only three years), as other long-term studies in China have shown a great potential of underground water contamination with nitrate-N from annual applications of FYM at relatively high rates [3,4,44]. Our findings also suggest the need for deep soil sampling, as soils in our study were sampled only to the 60 cm depth.

Earlier research in China has shown substantial increase in extractable P and total P in soil with long-term annual applications of FYM [5]. In our study, extractable P in the surface soil also increased considerably with compost even after three annual applications. Since wood ash contains fairly high concentration of P, there was moderate increase of extractable P in soil with wood ash. The substantial increase of extractable P with increasing rate of compost but only in the 0 - 15 cm soil layer suggests that P is relatively immobile, but our findings suggest very high build-up of P in the surface soil, especially after repeated applications of compost manure to increase crop production, and subsequently potential risk of contamination of surface waters with P from surface run-off of water after snow melt in early spring and/or after heavy rainfall events which often occur in this region during summer.

Previous research in China showed substantial decline in exchangeable K in soil over years in the control without any K addition, but this decrease in exchangeable K was ameliorated to some extent with continuous annual applications of FYM [5]. Similarly, in our study exchangeable K in soil increased with application of compost, wood ash and alfalfa pellets, as these amendments contain high concentrations of K. Like extractable P, considerable increase of exchangeable K with increasing rate of alfalfa pellets only in the 0 - 15 cm layer suggests that K is also relatively less mobile in soil and large accumulations of K can be expected after repeated applications of these amendments over many years.

Sulphate-S in soil increased with wood ash, and more so with compost and/or gypsum at both sites. This was due to the fact that gypsum contained sulphate-S and compost possibly increased sulphate-S through mineralization of organic matter. Sulphate-S increased with increasing rate of compost in both soils, but mainly in the 30 - 60 cm soil layer. It is possible that most of the sulphate-S in surface soil layers moved downward to 30 - 60 cm layer, especially due to much above-average precipitation in the third growing season in 2010. It is also possible that sulphate-S may have leached below the 60 cm depth, as evidenced by large amounts of sulphate-S in the 30 - 60 cm layer although no soil samples were obtained below 60 cm to verify this. This suggests the need for future soil sampling to greater depths in order to make valid conclusions related to sulphate-S leaching.

5. CONCLUSION

Organic C and N, N-supplying power (N_{min}), pH and residual available nutrients (N, P, K and S) in soil increased with compost and/or alfalfa pellets, but the magnitude of increase varied with amendment and/or soil type. In summary, our findings suggest that soil quality and fertility can be improved with these organic amendments, while also increasing sustainability of production from organic crops.

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