

Relative Effectiveness of Various Amendments in Improving Yield and Nutrient Uptake under Organic Crop Production

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Received July 5th, 2012; revised July 8th, 2012; accepted July 19th, 2012

ABSTRACT

In organic farming, artificial/synthetic inorganic fertilizers/chemicals are not applied to increase crop yields, but adequate amounts of nutrients are essential for sustainable high production from agricultural crops. Two 3-year (2008—wheat, 2009—pea, and 2010—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 to determine the relative effectiveness of various organic amendments (compost, alfalfa pellets, wood ash, rock phosphate, *Penicillium bilaiae*, MykePro, or gypsum), and intercropping of non-legume (wheat, barley) and legume (pea) annual crops on seed yield, total biomass yield (TBY) and nutrient uptake in seed + straw of wheat, pea and barley. In 2008, seed yield, TBY and nutrient uptake of wheat increased (but small) with compost and alfalfa pellets. In 2010, seed yield, TBY and nutrient uptake of barley increased substantially with compost and alfalfa pellets and moderately with wood ash. Other amendments had little or no effect on crop yield and nutrient uptake. In 2009, there was no beneficial effect of any amendment on yield and nutrient uptake of pea, most likely due to fixation of N which is the most limiting nutrient in these soils. Intercropping of wheat or barley with pea produced greater seed yield and nutrient uptake per unit land area basis compared to wheat or barley grown as sole crops in most cases. In conclusion, our results suggest potential benefits in improving yield and nutrient uptake of wheat and barley from compost, alfalfa pellets and possibly wood ash, most likely by preventing deficiencies of some nutrients, especially N, lacking in these soils under organic farming. Our findings also suggest the need for future research to determine the feasibility of rock phosphate, *Penicillium bilaiae*, MykePro, gypsum or other amendments in preventing P and/or S deficiency in organic crops using soils extremely deficient in these nutrients.

Keywords: Amendments; Barley; Nutrient Uptake; Organic; Pea; Wheat; Yield

1. Introduction

The interest and demand for organically-grown food and fiber are increasing in Canada [1] and internationally, because of possible high economic returns due to the price premiums on organically-grown products [2]. In organic farming, synthetic fertilizers/chemicals are not allowed to prevent nutrient deficiencies and increase crop production. However, adequate amounts of nutrients are essential for sustainable high production from agricultural crops, because any nutrient limiting in soil can cause substantial reduction in crop yield. The availability of plant nutrients to crops depends on crop species/cultivar, soil type and climatic conditions. In the Canadian Prairies, under organically farmed cropping systems most soils are deficient in available N, many soils are low in available P, and some soils contain insufficient amounts

of available S (mostly in the Parkland region) and available K for optimum crop growth and yield [3,4]. Research comparing both organic and conventional cropping systems in Saskatchewan has suggested that on soils low in available P, long-term production of organic crops without adding adequate amounts of P can result in the decrease/depletion of available P in soil by removing/mining P in seed away from the field [5]. Recent research in Montana, USA [6] has also indicated the decrease in nutrients in organically managed soils, resulting in poor crop yield and produce quality. Therefore, maintaining soil fertility is an important production issue facing organic agriculture in the semi-arid region of the Canadian Prairies and elsewhere.

Because N is the most limiting/deficient nutrient in most soils for optimum yield, organic producers usually focus on increasing N availability and minimizing N de-

iciency in soil-crop system on organic farms by growing N-fixing legume crops for grain, forage and/or green manure in the rotations [7,8]. However, if soils are deficient in available P, K, S or other essential nutrients, the only alternative is to use external organic sources to prevent these nutrient deficiencies, which can be inconvenient and/or expensive. For example, manure/compost can provide these nutrients to crops on organic farms, but often there is not enough manure to apply on all farm fields, especially in remote areas where the cost of transporting manure/compost to long distances can be uneconomical [9]. On such soils, rock phosphate fertilizer, elemental S fertilizer, gypsum, wood ash (wood ash is a waste product of forest industry that contains large amounts of Ca and Mg, about 0.44% P, 4.2% K, 1% S, and small amounts of other essential nutrients) or some other amendments may be used to correct nutrient deficiencies in organic crops.

In addition, crop yields on organic farms can be increased (also called out-yielding) by intercropping non-legume and legume annual crops together [10,11]. Out-yielding (*i.e.* when the yield produced by an intercrop is greater than the yield produced by the component crops grown in monoculture on the same total land area) can be calculated by using Land Equivalency Ratio (LER), which is defined as the relative land area under sole crops that is required to produce yields equivalent to intercropping [$LER = (\text{Intercrop1}/\text{Sole Crop1}) + \text{Intercrop2}/\text{Sole Crop2}$] as described by [12]. The LER values are used to compare growth/yield of intercrops relative to the respective sole crops. If the LER value is greater than 1, it indicates that out-yielding is occurring with intercropping, and the intercrop is more productive than the component crops grown as sole crops (*i.e.* less land requirement with intercropping compared to sole crops). If the LER is lower than 1, it suggests that there is no out-yielding occurring with intercropping (in fact under-yielding with intercropping), and the intercrop is less productive than the sole crops.

The information on the efficacy of organic nutrient sources and intercropping non-legume and legume annual crops in increasing yield by preventing nutrient deficiencies in crops is lacking under Canadian prairie soil-climatic conditions, especially in the Parkland region. The main objective of our study was to determine the relative effectiveness of various amendments (compost, alfalfa pellets, wood ash, rock phosphate, *Penicillium bilaiae*, gypsum and MykePro), and intercropping of non-legume (wheat, barley) and legume (pea) annual crops on yield and nutrient uptake of wheat, pea or barley organic crops and soil quality/fertility in northeastern Saskatchewan. The residual effects of these amendments on organic C and N, potentially mineralizable N (N_{\min})

and available nutrients (N, P, K and S) in soil are published in a previous paper [13], and the effects of these amendments on crop yield and uptake of N, P, K and S in the present study are reported in this paper.

2. Materials and Methods

Two 3-year (2008—wheat, 2009—pea, and 2010—barley) 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. 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. At Spalding, the land has been under certified organic farming practice for 21 years, with barley, hard red spring wheat, oat, fall rye, flax, lentil and pea generally grown in various rotations including green manure and/or summer fallow. At Star City, barley, hard red spring wheat, spelt wheat, oat, fall rye, flax, yellow mustard, polish canola, and pea have been usually grown in various rotations including green manure and/or summer fallow under certified organic farming practice for 15 years. Some characteristics of soils used in these experiments are presented in **Table 1**. Soil was low in available N at both sites. Based on soil type and agroecological region, the soil was suspected to be potentially deficient in available P in Experiment 1 at Spalding and available S in Experiment 2 at Star City. Precipitation in the growing season (May, June, July and August) at the two sites from 2008 to 2010, and long-term (30-year) average of precipitation and air temperature in May to August at the nearest Environment Canada Meteorological Station (AAFC Melfort Research Farm) are presented in **Table 2**. 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, the 23 treatments were: 1. Control (no amendment), 2. Compost @ 10 Mg·ha⁻¹, 3. Compost @ 20 Mg·ha⁻¹, 4. Compost @ 30 Mg·ha⁻¹, 5. Wood ash @ 1 Mg·ha⁻¹, 6. Wood ash @ 2 Mg·ha⁻¹, 7. Wood ash @ 3 Mg·ha⁻¹, 8. Rock phosphate granular @ 10 kg·P·ha⁻¹, 9. Rock phosphate granular @ 20 kg·P·ha⁻¹, 10. Rock phosphate granular @ 30 kg·P·ha⁻¹, 11. Rock phosphate finely-ground @ 10 kg·P·ha⁻¹, 12. Rock phosphate finely-

Table 1. Some characteristics of soils of field experiments in spring 2008, 2009 and 2010 at Spalding and Star City in north-eastern Saskatchewan.

Site	Year	Soil great group ^z	Depth (cm)	Texture ^y	pH ^x	Organic matter (%)	Nitrate-N (mg·kg ⁻¹)	Extractable P (mg·kg ⁻¹)	Sulphate-S (mg·kg ⁻¹)	Extractable K (mg·kg ⁻¹)
Spalding	2008	Dark Brown	0 - 15	SL	7.1	2.4	8.8	8.3	3.8	141
			15 - 30				3.9	3.9	2.6	99
			30 - 60				2.4	2.1	2.0	82
	2009		0 - 15	SL	nd	nd	5.2	6.3	2.6	163
			15 - 30				1.6	5.4	0.6	147
			30 - 60				1.8	3.7	0.1	124
	2010		0 - 15	SL	nd	nd	3.6	7.6	2.1	184
			15 - 30				0.9	5.5	1.4	141
			30 - 60				0.8	4.7	0.8	121
Star City	2008	Gray luvisol	0 - 15	L	6.2	1.8	10.7	8.6	2.8	154
			15 - 30				3.2	5.4	2.4	116
			30 - 60				1.7	5.5	1.2	115
	2009		0 - 15	L	nd	nd	14.0	11.8	2.3	182
			15 - 30				2.2	5.2	0.6	131
			30 - 60				1.4	5.8	0.3	129
	2010		0 - 15	L	nd	nd	7.2	9.7	2.4	216
			15 - 30				1.5	7.2	1.4	129
			30 - 60				2.0	6.3	1.7	114

^zBased on Canadian Soil Classification System. ^ySL and L refer to sandy loam and loam, respectively; ^xnd refers to not done in 2009 and 2010, as soil pH and organic matter do not change frequently in the absence of amendments.

Table 2. Growing season monthly and total precipitation for the four site-years, and average 30-yr average precipitation and temperature in northeastern Saskatchewan.

Month	Precipitation in the growing season (mm) ^z						30-yr average	
	Spalding			Star City			Precipitation (mm)	Temperature (°C)
	2008	2009	2010	2008	2009	2010		
May	15.0	10.9	103.2	6.2	21.2	66.6	45.6	9.1
June	29.0	91.8	130.0	32.0	46.6	113.2	65.8	16.9
July	90.6	67.8	51.0	118.4	75.6	63.6	75.5	18.3
August	31.2	82.0	83.0	21.6	81.6	56.8	56.8	19.6
Total	165.8	252.5	367.2	178.2	225.0	300.2	243.7	

^zAt the nearest Environment Canada Meteorological Station (Muenster for Spalding and Melfort Research Farm for Star City).

ground @ 20 kg·P·ha⁻¹, 13. Rock phosphate finely-ground @ 30 kg·P·ha⁻¹, 14. Alfalfa pellets @ 1 Mg·ha⁻¹, 15. Alfalfa pellets @ 2 Mg·ha⁻¹, 16. Alfalfa pellets @ 4 Mg·ha⁻¹, 17. Alfalfa pellets @ 6 Mg·ha⁻¹, 18. Control + inoculate seed with *Penicillium bilaiae*, 19. Rock phosphate granular @ 20 kg·P·ha⁻¹ + inoculate seed with *Penicillium bilaiae*, 20. Rock phosphate finely-ground @ 20 kg·P·ha⁻¹ + inoculate seed with *Penicillium bilaiae*, 21. Pulse (no amendment), 22. Cereal + pulse intercrop (no amendment), and 23. MykePro.

In Experiment 2, the 21 treatments were: 1. Control (no amendment), 2. Compost @ 10 Mg·ha⁻¹, 3. Compost @ 20 Mg·ha⁻¹, 4. Compost @ 30 Mg·ha⁻¹, 5. Wood ash @ 1 Mg·ha⁻¹, 6. Wood ash @ 2 Mg·ha⁻¹, 7. Wood ash @ 3 Mg·ha⁻¹, 8. Alfalfa pellets @ 1 Mg·ha⁻¹, 9. Alfalfa pellets @ 2 Mg·ha⁻¹, 10. Alfalfa pellets @ 4 Mg·ha⁻¹, 11. Alfalfa pellets @ 6 Mg·ha⁻¹, 12. Gypsum @ 10 kg·S·ha⁻¹, 13. Gypsum @ 20 kg·S·ha⁻¹, 14. Pulse (no amendment), 15. Cereal + pulse intercrop (no amendment), 16. Control + inoculate seed with *Penicillium bilaiae*, 17. Rock pho-

sphate finely-ground @ 20 kg·P·ha⁻¹, 18. Rock phosphate finely-ground @ 20 kg·P·ha⁻¹ + inoculate seed with *Penicillium bilaiae*, 19. Rock phosphate granular @ 20 kg·P·ha⁻¹, 20. Rock phosphate granular @ 20 kg·P·ha⁻¹ + inoculate seed with *Penicillium bilaiae*, and 21. Myke-Pro.

On average, compost contained 1.3% N, 0.64% P, 1.3% and 0.3% S; alfalfa pellets had 2.9% N, 0.20% P, 2.5% and 0.2% S; and wood ash contained 0.51% P, 4.5% and 1.3% S. Rock phosphate contained 7.4% P and gypsum had 12% S. *Penicillium bilaiae* and MykePro do not supply any nutrients directly to soil/plant, but these inoculants are applied to increase the release of P from soil and/or rock phosphate for plant uptake. The amendments were broadcast on soil surface and all plots were rotovated to a depth of about 8 cm few days prior to seeding. Plots were seeded with a double-disc press drill at 17.8 cm row spacing. In each plot, a 1.25 m wide by 7.0 m long strip was harvested with a plot combine to determine seed yield. Straw yield was calculated from two 1-m long rows, hand harvested from each plot. Sub samples of seed and straw were oven dried (60°C), and

analyzed for total N [14], total P [15], total K [16] and total S [17].

The data on each parameter were subjected to analyses of variance (ANOVA) using GLM procedure in SAS [18]. The least significant difference at $P \leq 0.05$ (LSD_{0.05}) was used to determine significant differences between treatment means. For the convenience of the readers, the results on treatments with wheat or barley intercropped with pea, or grown as sole crops without any amendment are reported and discussed separately. In all other amendment treatments, there was only one crop in a growing season, *i.e.*, wheat in 2008, pea 2009, or barley in 2010.

3. Results

3.1. Experiment 1 at Spalding

3.1.1. Yield

In 2008, seed yield of wheat increased with compost and tended to increase with alfalfa pellets at higher rates in the first year of application (**Table 3**). However, application of *Penicillium bilaiae*, rock phosphate fertilizer

Table 3. Seed yield and total biomass yield (TBY) of wheat (2008), pea (2009) and barley (2010) with various amendments applied annually in spring of 2008, 2009 and 2010 at Spalding, Saskatchewan (Experiment 1).

Treatment		Seed yield (kg·ha ⁻¹)			TBY (kg·ha ⁻¹)		
No.	Amendments	2008 wheat	2009 pea	2010 barley	2008 wheat	2009 pea	2010 barley
1	Control (no amendment)	1902	3423	1253	5930	5159	4267
2	Compost @ 10 Mg·ha ⁻¹	1927	3799	2385	5669	5774	5530
3	Compost @ 20 Mg·ha ⁻¹	2146	3179	2576	6657	5314	6100
4	Compost @ 30 Mg·ha ⁻¹	2189	3326	2874	6186	5541	6747
5	Wood ash @ 1 Mg·ha ⁻¹	1743	3198	1827	5634	5081	4034
6	Wood ash @ 2 Mg·ha ⁻¹	1847	3102	1779	5606	4938	4415
7	Wood ash @ 3 Mg·ha ⁻¹	1951	3027	1820	5786	4648	4511
8	Rock phosphate granular @ 10 kg·P·ha ⁻¹	1635	3393	1601	5304	5239	3809
9	Rock phosphate granular @ 20 kg·P·ha ⁻¹	1757	3347	1526	5548	5213	3496
10	Rock phosphate granular @ 30 kg·P·ha ⁻¹	1871	3051	1659	5527	4686	4336
11	Rock phosphate finely-ground @ 10 kg·P·ha ⁻¹	1717	3177	1203	5277	4903	3743
12	Rock phosphate finely-ground @ 20 kg·P·ha ⁻¹	1815	3252	1368	5654	5025	4047
13	Rock phosphate finely-ground @ 30 kg·P·ha ⁻¹	1880	3226	1283	5943	4849	3736
14	Alfalfa pellets @ 1 Mg·ha ⁻¹	1817	2968	1432	5633	4732	4100
15	Alfalfa pellets @ 2 Mg·ha ⁻¹	1954	2787	1693	5822	4515	4406
16	Alfalfa pellets @ 4 Mg·ha ⁻¹	2083	2345	2174	6271	4171	5521
17	Alfalfa pellets @ 6 Mg·ha ⁻¹	2079	1785	2128	6814	3934	4566
18	Control + <i>Penicillium bilaiae</i>	1823	3076	1306	5677	5013	3162
19	Rock phosphate granular @ 20 kg·P·ha ⁻¹ + <i>Penicillium bilaiae</i>	1853	3372	1534	5892	4821	3560
20	Rock phosphate finely-ground @ 20 kg·P·ha ⁻¹ + <i>Penicillium bilaiae</i>	1854	3150	1462	5934	4895	4144
23	MykePro	1896	3279	1412	5889	5132	3767
	LSD _{0.05}	229	534	332	754	706	1090
	SEM ^z	80.9***	188.7***	117.0***	266.5 [†]	249.5**	383.7***

^z, [†], ^{**} and ^{***} refer to significant treatment effects in ANOVA at $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$, respectively.

without and with *Penicillium bilaiae*, and MykePro had no beneficial effect on seed yield of wheat, and seed yields were similar to the zero-amendment control. In 2009, there was no significant increase in seed yield of pea from the application of any amendment in the second year of application (Table 3). In fact, seed yield of pea decreased with increasing rate of alfalfa pellets. In 2010, seed yield of barley increased considerably with compost, followed by alfalfa pellets especially at higher rates, and moderately with wood ash (Table 3). Seed yield of barley tended to increase (not significant) with granular rock phosphate, but seed yields in finely-ground rock phosphate, *Penicillium bilaiae* and MykePro treatments were similar to the control. Total biomass yield (TBY) usually followed response trends similar to seed yield, with increase in TBY from compost or alfalfa pellets but no consistent increase in TBY from wood ash and other amendments (Table 3).

3.1.2. Nutrient Uptake

In 2008, uptake of total N, K and S in seed + straw of

wheat increased with application of alfalfa pellets at high rates (Tables 4 and 5). Total N, K and S uptake in seed + straw of wheat tended to increase with application of compost. This suggested that alfalfa pellets and possibly compost supplied N, K and S for plant uptake in the first year of application. In 2009, total N, K and S uptake in seed + straw usually increased with compost, but no consistent effect from other amendments (Tables 4 and 5). In 2010, total N, K and S uptake in seed + straw increased considerably with compost and moderately with alfalfa pellets, but no effect from other amendments (Tables 4 and 5). Total P uptake in seed + straw of wheat in 2008 increased with increasing rate of alfalfa pellets and compost, but the increases were small and not significant (Table 4). In 2009, total P uptake in seed + straw of pea increased with application of compost, but decreased with increasing rate of alfalfa pellets (Table 4). In 2010, total P uptake of barley in seed + straw increased considerably with compost, but no consistent effect from other amendments (Table 4).

Table 4. Total N and P uptake in seed + straw of wheat (2008), pea (2009) and barley (2010) with various amendments applied annually in spring of 2008, 2009 and 2010 at Spalding, Saskatchewan (Experiment 1).

Treatment		Total N uptake in seed + straw (kg·N·ha ⁻¹)			Total P uptake in seed + straw (kg·P·ha ⁻¹)		
No.	Amendments	2008 wheat	2009 pea	2010 barley	2008 wheat	2009 pea	2010 barley
1	Control (no amendment)	51.2	127.7	41.1	10.1	13.0	10.3
2	Compost @ 10 Mg·ha ⁻¹	47.3	144.6	53.1	10.2	17.1	15.5
3	Compost @ 20 Mg·ha ⁻¹	54.3	137.8	60.9	11.8	18.0	16.0
4	Compost @ 30 Mg·ha ⁻¹	54.5	143.8	71.4	11.5	18.8	19.1
5	Wood ash @ 1 Mg·ha ⁻¹	46.0	125.2	40.1	9.6	11.2	9.9
6	Wood ash @ 2 Mg·ha ⁻¹	50.2	116.1	42.0	9.7	10.1	10.5
7	Wood ash @ 3 Mg·ha ⁻¹	50.7	113.2	41.8	9.3	10.2	11.0
8	Rock phosphate granular @ 10 kg·P·ha ⁻¹	43.3	129.9	38.4	8.6	12.4	9.4
9	Rock phosphate granular @ 20 kg·P·ha ⁻¹	45.7	126.3	36.4	8.3	11.2	8.8
10	Rock phosphate granular @ 30 kg·P·ha ⁻¹	51.6	111.2	44.7	9.3	9.3	9.3
11	Rock phosphate finely-ground @ 10 kg·P·ha ⁻¹	44.0	115.3	37.6	8.4	10.4	8.7
12	Rock phosphate finely-ground @ 20 kg·P·ha ⁻¹	50.1	118.9	42.5	9.2	10.3	9.8
13	Rock phosphate finely-ground @ 30 kg·P·ha ⁻¹	49.7	118.3	38.3	9.7	10.8	9.3
14	Alfalfa pellets @ 1 Mg·ha ⁻¹	49.8	105.2	41.1	9.3	10.1	9.3
15	Alfalfa pellets @ 2 Mg·ha ⁻¹	52.9	100.2	44.3	9.7	8.7	9.6
16	Alfalfa pellets @ 4 Mg·ha ⁻¹	62.6	89.7	56.3	10.8	8.3	11.7
17	Alfalfa pellets @ 6 Mg·ha ⁻¹	68.6	73.9	56.1	11.1	6.8	9.7
18	Control + <i>Penicillium bilaiae</i>	48.5	117.4	35.6	9.2	10.3	8.0
19	Rock phosphate granular @ 20 kg·P·ha ⁻¹ + <i>Penicillium bilaiae</i>	49.3	121.4	37.5	9.9	11.1	8.3
20	Rock phosphate finely-ground @ 20 kg·P·ha ⁻¹ + <i>Penicillium bilaiae</i>	51.4	118.5	43.1	9.8	10.2	9.2
23	MykePro	52.9	118.7	39.8	10.1	11.0	9.1
	LSD _{0.05}	7.3	20.8	9.2	1.6	3.2	2.5
	SEM ^c	2.58 ^{***}	7.36 ^{***}	3.23 ^{***}	0.55 ^{***}	1.4 ^{***}	0.90 ^{***}

^{z***} refers to significant treatment effects in ANOVA at P ≤ 0.001.

Table 5. Total K and S uptake in seed + straw of wheat (2008), pea (2009) and barley (2010) with various amendments applied annually in spring of 2008, 2009 and 2010 at Spalding, Saskatchewan (Experiment 1).

Treatment		Total K uptake in seed + straw (kg·K·ha ⁻¹)			Total S uptake in seed + straw (kg·S·ha ⁻¹)		
No.	Amendments	2008 wheat	2009 pea	2010 barley	2008 wheat	2009 pea	2010 barley
1	Control (no amendment)	50.1	54.1	45.7	4.7	5.3	3.8
2	Compost @ 10 Mg·ha ⁻¹	47.5	74.1	62.7	4.5	9.2	5.5
3	Compost @ 20 Mg·ha ⁻¹	57.8	76.1	76.9	5.6	10.0	6.2
4	Compost @ 30 Mg·ha ⁻¹	53.0	83.7	82.1	5.4	10.6	7.3
5	Wood ash @ 1 Mg·ha ⁻¹	48.7	59.9	35.5	4.9	6.6	4.1
6	Wood ash @ 2 Mg·ha ⁻¹	48.8	60.5	42.3	5.2	6.7	4.5
7	Wood ash @ 3 Mg·ha ⁻¹	50.9	54.4	43.9	5.2	6.6	4.7
8	Rock phosphate granular @ 10 kg·P·ha ⁻¹	43.1	58.7	35.1	4.0	5.5	3.5
9	Rock phosphate granular @ 20 kg·P·ha ⁻¹	44.5	58.0	33.5	4.3	5.6	3.4
10	Rock phosphate granular @ 30 kg·P·ha ⁻¹	50.1	49.2	41.3	4.8	5.2	4.3
11	Rock phosphate finely-ground @ 10 kg·P·ha ⁻¹	42.1	51.0	37.0	3.9	5.0	3.6
12	Rock phosphate finely-ground @ 20 kg·P·ha ⁻¹	50.4	53.9	44.4	4.9	5.4	4.2
13	Rock phosphate finely-ground @ 30 kg·P·ha ⁻¹	50.6	51.0	41.9	4.8	5.2	3.6
14	Alfalfa pellets @ 1 Mg·ha ⁻¹	46.4	51.8	45.5	4.6	5.1	3.9
15	Alfalfa pellets @ 2 Mg·ha ⁻¹	47.8	49.1	48.1	4.9	4.6	4.1
16	Alfalfa pellets @ 4 Mg·ha ⁻¹	63.4	50.0	62.7	5.7	4.6	5.0
17	Alfalfa pellets @ 6 Mg·ha ⁻¹	66.0	52.9	48.3	6.6	4.2	4.5
18	Control + <i>Penicillium bilaiae</i>	45.4	53.3	29.4	4.7	5.4	3.2
19	Rock phosphate granular @ 20 kg·P·ha ⁻¹ + <i>Penicillium bilaiae</i>	51.7	51.1	32.8	4.7	5.1	3.6
20	Rock phosphate finely-ground @ 20 kg·P·ha ⁻¹ + <i>Penicillium bilaiae</i>	50.4	52.5	44.8	5.0	5.4	3.9
23	MykePro	51.1	56.4	38.1	5.1	5.6	3.8
	LSD _{0.05}	9.9	9.9	17.3	0.8	1.0	1.0
	SEM ^z	3.50 ^{***}	3.52 ^{***}	6.11 ^{***}	0.27 ^{***}	0.34 ^{***}	0.37 ^{***}

^{z***} refers to significant treatment effects in ANOVA at $P \leq 0.001$.

3.2. Experiment 2 at Star City

3.2.1. Yield

In 2008, because of severe infestation of the experimental site with wild oat, seed yield of wheat was very low in all treatments (Table 6). Seed yield of wheat increased with application of compost and alfalfa pellets in most cases over the zero-amendment control, but there was little or no increase in seed yield with other amendments. The TBYS of wheat were moderately high, and there was a good response of TBYS to compost, followed by alfalfa pellets and MykePro, but little or no increase from other amendments. In 2009, due to infestation with wild oat again, seed yields of pea were relatively low, but TBYS were fairly high (Table 6). Both seed yield and TBYS of pea increased only with application of compost over the control. In 2010, seed yield and TBYS of barley

increased considerably with application of compost and alfalfa pellets over the control (Table 6). There was also an improvement in seed yield and TBYS of barley (small, but significant) with application of wood ash at high rates. Seed yield of wild oat was higher in treatments receiving compost and alfalfa pellets compared to the control in all three years (data not shown).

3.2.2. Nutrient Uptake

In 2008 and 2009, total N, P, K and S uptake in seed + straw increased with increasing rate of compost and also increased with alfalfa pellets at high rates (Tables 7 and 8). In 2010, total N, P, K and S uptake of barley in seed + straw increased considerably with application of compost and alfalfa pellets over the zero-amendment control (Tables 7 and 8). There was also a tendency of increase in total N, P, K and S uptake in seed + straw of barley

Table 6. Seed yield and total biomass yield (TBY) of wheat (2008), pea (2009) and barley (2010) with various amendments applied annually in spring of 2008, 2009 and 2010 at Star City, Saskatchewan (Experiment 2).

No.	Treatment	Seed yield (kg·ha ⁻¹)			TBY (kg·ha ⁻¹)		
		2008 wheat	2009 pea	2010 barley	2008 wheat	2009 pea	2010 barley
1	Control (no amendment)	264	668	2233	3237	4893	5005
2	Compost @ 10 Mg·ha ⁻¹	435	796	3359	3905	5546	7501
3	Compost @ 20 Mg·ha ⁻¹	470	965	3570	4611	5360	8216
4	Compost @ 30 Mg·ha ⁻¹	580	1180	3671	5069	6379	8126
5	Wood ash @ 1 Mg·ha ⁻¹	305	765	2348	3897	4574	4831
6	Wood ash @ 2 Mg·ha ⁻¹	341	760	2705	3695	5009	5489
7	Wood ash @ 3 Mg·ha ⁻¹	315	791	2804	3980	5030	6230
8	Alfalfa pellets @ 1 Mg·ha ⁻¹	377	493	2663	3909	3901	5716
9	Alfalfa pellets @ 2 Mg·ha ⁻¹	340	585	2872	3837	4565	5863
10	Alfalfa pellets @ 4 Mg·ha ⁻¹	400	629	3859	4032	4782	8441
11	Alfalfa pellets @ 6 Mg·ha ⁻¹	429	726	4067	4322	5747	9577
12	Gypsum @ 10 kg·S·ha ⁻¹	391	758	2110	3855	4421	4540
13	Gypsum @ 20 kg·S·ha ⁻¹	328	633	2103	3750	4480	4685
16	Control + <i>Penicillium bilaiae</i>	319	691	2128	3635	3635	4638
17	Rock phosphate finely-ground @ 20 kg·P·ha ⁻¹	271	619	2170	3116	4292	4720
18	Rock phosphate finely-ground @ 20 kg·P·ha ⁻¹ + <i>Penicillium bilaiae</i>	317	663	2133	3987	4639	4761
19	Rock phosphate granular @ 20 kg·P·ha ⁻¹	317	592	2323	3719	4198	5020
20	Rock phosphate granular @ 20 kg·P·ha ⁻¹ + <i>Penicillium bilaiae</i>	347	589	2227	3775	4138	4772
21	MykePro	341	626	2202	4245	4195	4342
	LSD _{0.05}	92	221	367	834	903	941
	SEM ^z	32.3***	77.9***	129.3***	294.1*	318.4***	331.9***

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

Table 7. Total N and P uptake in seed + straw of wheat (2008), pea (2009) and barley (2010) with various amendments applied annually in spring of 2008, 2009 and 2010 at Star City, Saskatchewan (Experiment 2).

No.	Treatment	Total N uptake in seed + straw (kg·N·ha ⁻¹)			Total P uptake in seed + straw (kg·P·ha ⁻¹)		
		2008 wheat	2009 pea	2010 barley	2008 wheat	2009 pea	2010 barley
1	Control (no amendment)	34.6	46.5	57.7	4.6	6.7	13.1
2	Compost @ 10 Mg·ha ⁻¹	42.0	57.0	76.8	6.3	9.3	19.8
3	Compost @ 20 Mg·ha ⁻¹	44.0	62.5	84.4	7.9	10.5	22.4
4	Compost @ 30 Mg·ha ⁻¹	48.8	75.0	89.4	8.9	12.8	23.8
5	Wood ash @ 1 Mg·ha ⁻¹	38.9	48.9	51.1	5.2	7.3	13.8
6	Wood ash @ 2 Mg·ha ⁻¹	35.7	52.5	56.9	5.4	8.3	15.0
7	Wood ash @ 3 Mg·ha ⁻¹	41.7	51.3	64.4	6.0	7.9	16.5
8	Alfalfa pellets @ 1 Mg·ha ⁻¹	39.2	36.6	63.4	5.0	5.7	15.0
9	Alfalfa pellets @ 2 Mg·ha ⁻¹	38.1	43.3	66.9	5.7	6.6	15.3
10	Alfalfa pellets @ 4 Mg·ha ⁻¹	42.7	47.6	94.9	5.4	6.8	19.5
11	Alfalfa pellets @ 6 Mg·ha ⁻¹	49.4	62.5	114.6	6.6	7.8	21.4
12	Gypsum @ 10 kg·S·ha ⁻¹	41.1	48.0	55.1	5.7	6.4	12.7
13	Gypsum @ 20 kg·S·ha ⁻¹	36.0	43.9	53.8	4.8	6.5	13.0
16	Control + <i>Penicillium bilaiae</i>	34.6	40.8	53.1	4.5	5.9	13.1
17	Rock phosphate finely-ground @ 20 kg·P·ha ⁻¹	29.3	43.7	53.2	4.2	6.9	13.2
18	Rock phosphate finely-ground @ 20 kg·P·ha ⁻¹ + <i>Penicillium bilaiae</i>	35.4	45.7	54.7	5.9	8.0	13.9
19	Rock phosphate granular @ 20 kg·P·ha ⁻¹	31.5	40.4	55.2	5.5	6.9	14.1
20	Rock phosphate granular @ 20 kg·P·ha ⁻¹ + <i>Penicillium bilaiae</i>	37.5	39.6	52.6	5.4	6.6	13.6
21	MykePro	40.4	43.2	52.4	6.2	7.0	13.1
	LSD _{0.05}	8.7	9.6	10.6	1.4	1.5	2.1
	SEM ^z	3.07***	3.37***	3.73***	0.50***	0.52***	0.74***

^z*** refers to significant treatment effects in ANOVA at P ≤ 0.001.

Table 8. Total K and S uptake in seed + straw of wheat (2008), pea (2009) and barley (2010) with various amendments applied annually in spring of 2008, 2009 and 2010 at Star City, Saskatchewan (Experiment 2).

Treatment		Total K uptake in seed + straw (kg·K·ha ⁻¹)			Total S uptake in seed + straw (kg·S·ha ⁻¹)		
No.	Amendments	2008 wheat	2009 pea	2010 barley	2008 wheat	2009 pea	2010 barley
1	Control (no amendment)	48.0	77.4	40.1	3.1	5.1	5.4
2	Compost @ 10 Mg·ha ⁻¹	49.5	93.4	71.0	3.9	12.6	7.5
3	Compost @ 20 Mg·ha ⁻¹	56.0	96.9	89.0	4.7	13.3	8.5
4	Compost @ 30 Mg·ha ⁻¹	64.2	123.5	88.5	4.8	16.9	8.6
5	Wood ash @ 1 Mg·ha ⁻¹	56.3	76.5	38.2	4.5	8.5	5.1
6	Wood ash @ 2 Mg·ha ⁻¹	53.3	87.3	45.2	4.0	10.8	5.9
7	Wood ash @ 3 Mg·ha ⁻¹	54.1	87.4	54.3	4.8	11.5	6.5
8	Alfalfa pellets @ 1 Mg·ha ⁻¹	54.0	62.7	48.1	3.7	4.3	5.8
9	Alfalfa pellets @ 2 Mg·ha ⁻¹	55.3	72.6	49.8	3.4	4.6	5.9
10	Alfalfa pellets @ 4 Mg·ha ⁻¹	58.6	83.9	79.3	3.9	4.9	8.0
11	Alfalfa pellets @ 6 Mg·ha ⁻¹	59.9	111.6	109.3	4.4	5.8	9.3
12	Gypsum @ 10 kg·S·ha ⁻¹	52.2	70.9	39.2	4.1	6.4	5.4
13	Gypsum @ 20 kg·S·ha ⁻¹	50.3	74.6	38.7	3.9	8.5	5.8
16	Control + <i>Penicillium bilaiae</i>	46.5	55.1	37.3	3.2	3.8	4.8
17	Rock phosphate finely-ground @ 20 kg·P·ha ⁻¹	37.8	66.1	37.2	2.8	4.7	4.8
18	Rock phosphate finely-ground @ 20 kg·P·ha ⁻¹ + <i>Penicillium bilaiae</i>	48.0	74.9	41.7	3.2	4.8	5.0
19	Rock phosphate granular @ 20 kg·P·ha ⁻¹	47.4	66.9	42.9	3.2	4.3	5.1
20	Rock phosphate granular @ 20 kg·P·ha ⁻¹ + <i>Penicillium bilaiae</i>	50.3	66.4	38.2	3.6	4.8	5.0
21	MykePro	57.5	70.8	36.4	4.0	4.3	4.8
	LSD _{0.05}	17.6	18.7	12.0	1.0	2.2	0.9
	SEM ^z	6.22 ^{ns}	6.59 ^{***}	4.22 ^{***}	0.35 ^{***}	0.79 ^{***}	0.32 ^{***}

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

with wood ash. The results suggested that N, P, K and S in compost and alfalfa pellets became available to the crop in all three growing seasons. There was no increase in total N uptake in seed + straw from the application of other amendments.

3.3. Cereal-pea Intercropping

3.3.1. Experiment 1 at Spalding

At Spalding, seed yield was lower with pea alone, but greater with wheat alone than wheat-pea intercrop in 2008 (Table 9). The order of seed yield was pea alone < wheat + pea intercrop < wheat alone. The LER for wheat-pea intercrop was 1.08 (0.62 + 0.46), suggesting 8% less land requirement for wheat-pea intercrop compared to wheat or pea grown as sole crops to produce the same seed yield. In 2009, barley alone and barley intercropped with pea produced lower seed yield than the pea alone (Table 9). The order of seed yield was pea alone > barley + pea intercrop > barley alone. The LER for

barley-pea intercrop was 0.96 (0.42 + 0.54), suggesting slightly higher land requirement for barley-pea intercrop compared to barley or pea grown as sole crops for the same seed yield. In 2010, seed yield of pea alone was highest, followed by barley-pea intercrop, with the lowest seed yield with barley alone (Table 9). The LER for barley-pea intercrop was 1.29 (0.73 + 0.56). This suggests 29% lower land requirement for barley-pea intercrop compared to barley or pea grown as sole crops for the same seed yield. The total biomass yield of various crops in all three years usually showed trends similar to seed yield (Table 9).

3.3.2. Experiment 2 at Star City

At Star City, seed yields were very low due to severe wild oat infestation in 2008, and the order of seed yield was pea alone < wheat + pea intercrop = wheat alone (Table 10). The LER for wheat-pea intercrop was 1.22 (0.68 + 0.54), suggesting 22% less land requirement for wheat-pea intercrop compared to wheat or pea grown as

Table 9. Seed yield and total biomass yield (TBY - seed + straw) of wheat, barley, or pea grown as sole crops and as intercrop (wheat-pea in 2008, and barley-pea in 2009 and 2010) without addition of any amendment in 2008, 2009 and 2010 at Spalding, Saskatchewan (Experiment 1).

Year/treatment					
Year	Treatment number	Sole crops versus intercrop	Seed yield (kg·ha ⁻¹)	TBY (kg·ha ⁻¹)	
2008	1	Wheat	1902	5930	
	21	Pea	762	3997	
	22	Wheat + pea	1532 (1180 + 352)	5191	
			LSD _{0.05}	267	690
			SEM	77.1***	199.3**
2009	1	Barley	766	1359	
	21	Pea	3423	5159	
	22	Barley + pea	2167 (324 + 1843)	3595	
			LSD _{0.05}	431	581
			SEM	124.6***	167.9***
2010	1	Barley	400	1400	
	21	Pea	1253	4267	
	22	Barley + pea	990 (293+697)	3018	
			LSD _{0.05}	486	1352
			SEM	123.7*	344.3*

*, ** and *** refer to significant treatment effects in ANOVA at $P \leq 0.10$, $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$, respectively.

Table 10. Seed yield and total biomass yield (TBY - seed + straw) of wheat, barley, or pea grown as sole crops and as intercrop (wheat-pea in 2008, and barley-pea in 2009 and 2010) without addition of any amendment in 2008, 2009 and 2010 at Star City, Saskatchewan (Experiment 2).

Year/treatment					
Year	Treatment number	Sole crops versus intercrop	Seed yield (kg·ha ⁻¹)	TBY (kg·ha ⁻¹)	
2008	1	Wheat	264	3237	
	14	Pea	71	3635	
	15	Wheat + pea	217 (179 + 38)	3829	
			LSD _{0.05}	66	836
			SEM	19.2**	241.7 ^{ns}
2009	1	Barley	1409	3799	
	14	Pea	668	4893	
	15	Barley + pea	886 (389+497)	4372	
			LSD _{0.05}	242	1004
			SEM	69.8***	290.1*
2010	1	Barley	2233	4905	
	14	Pea	2399	5005	
	15	Barley + pea	2569 (1234+1335)	4952	
			LSD _{0.05}	859	1519
			SEM	248.3 ^{ns}	439 ^{ns}

*, **, *** and ns refer to significant treatment effects in ANOVA at $P \leq 0.10$, $P \leq 0.01$, $P \leq 0.001$ and not significant, respectively.

sole crops to produce same seed yield. In 2009, barley alone produced greater, but barley intercropped with pea produced lower seed yield than the pea alone control (**Table 10**). The order of seed yield was barley alone > barley + pea intercrop > pea alone. The LER for barley-pea intercrop was 0.93 (0.35 + 0.58), suggesting slightly higher land requirement for barley-pea intercrop compared to barley or pea grown as sole crops for the same seed yield. In 2010, seed yield of barley-pea intercrop tended to be higher than sole crops of barley and pea (**Table 10**). The LER for barley-pea intercrop was 1.11 (0.55 + 0.56). This suggested that barley-pea intercrop had 11% lower land requirement compared to barley or pea grown as sole crops for the same seed yield. The total biomass yield showed trends similar to seed yield (**Table 10**).

4. Discussion

Earlier studies have shown potential beneficial effects of both organic and mineral/inorganic amendments (that are allowed as nutrient sources for certified organic production), and soil activators/inoculants on crop yields, produce quality and nutrient uptake [7,19-22]. Similarly, in our study a few amendments improved yield and nutrient uptake of crops grown on certified organic farms, and the results are discussed in detail by providing explanations in the following paragraphs.

Previous research has indicated that composted manure is a good supplier of N, P, K, S, and other nutrients, and is expected to increase crop yield when these nutrients are limiting in soil for optimum crop growth/development [23]. Similarly, in our study, composted manure and alfalfa pellets in many cases and also wood ash in some cases were effective in increasing crop yields in 2008 and 2010, when cereals were the test crops, and nutrient uptake in all years regardless of crop type. The increases in crop yields from various amendments were most likely by preventing some nutrient deficiencies in crops, especially N (the most yield limiting nutrient in soil at our experimental sites), as also suggested for manure by other researchers [23]. For alfalfa pellets, it is possible that narrow C:N ratio in plant materials of alfalfa pellets may have supplied N and other nutrients after mineralization [24]. In our other previous study for the same experimental sites on residual effects of amendments on soil properties [13], total and light fraction organic C and N, N_{min} , and available N, P, K or S in soil usually increased after three annual applications of compost, alfalfa pellets, wood ash or gypsum, depending on the amendment and site. Therefore, the increases in uptake of N, P, K or S in crops in the present study were due to the fact that these amendments supplied these nutrients for plant uptake, most likely by increasing nutrient

availability in soil due to improvement in soil fertility and also possibly by enhancing soil quality/tilth/health.

Crops with taproots can absorb nutrients from deeper soil layers [25], depending on the root length [26]. However, if the surface and sub-soil layers are low in available P, then it is very difficult to increase the availability of P on the farm site and sustain high crop production under organic farming systems, by using deep taproot crops in the rotation to bring P from deeper soil layers to the surface soil for future crop use [5]. So, the only alternative is to add external P source, which is acceptable and practical under organic farming. For example, previous research has suggested the use of vesiculararbuscular mycorrhiza (VAM), *Penicillium bilaiae*, rock phosphate, or bone meal to increase the release of P from soil and organic P fertilizers/amendments in order to prevent P deficiency in P-deficient soils and increase crop yields [19,21-22,27-28]. In a field study in Saskatchewan, Takeda [25] did not find any benefit of rock phosphate application on crop yield and P uptake over two years at any of the three sites, but showed increases in crop yield and P uptake at two sites from the application of rock phosphate in a combination with *Penicillium bilaiae*. Gleddie *et al.* [29] also reported positive responses to *Penicillium bilaiae* inoculation on soils that were extremely deficient in P for optimum growth. However, in our study on organic farms, there was no consistent significant beneficial effect of rock phosphate and/or *Penicillium bilaiae* on crop yield and P uptake in our study (with potentially P-deficient soil in Experiment 1) over three years. It is possible that our soils may not be deficient in available P to the level to limit crop yield under organic production, because of the possibility of low yield potential under organic farming, as suggested by Brandt *et al.* [23] when comparing organic and conventional cropping systems over 12 years. We expected increase in crop yield and/or P uptake from the finely ground rock phosphate, because of the increase in surface area, but it did not happen. As explained earlier, this could be due to low yield potential of organic crops, and possibly the finely ground rock phosphate may have also conferred physical or chemical changes in soil, which in turn may have affected the microbiological activities in soil. This may have resulted in immobilization/fixation of P from finely ground rock phosphate into the soil organic fraction and subsequently impacting plant growth negatively on this potentially low P soil. Thus, suggesting the need of future long-term investigation to determine the efficacy of rock phosphate, *Penicillium bilaiae*, MykePro and other amendments in preventing deficiency of P in organic crops on soils extremely deficient in available P for optimum yield.

Like P, if soil is low in available S, then the only al-

ternative is to add external S source that can be used under organic farming. Our previous research has suggested that gypsum can be a suitable source of S to prevent S deficiency in crops [30]. However, in our present study on organic farm, there was little effect of gypsum used in Experiment 2 (with potentially S-deficient soil at this site) on crop yield and S uptake in any of the three years. It is possible that our soil may not be deficient in available S to the extent that can limit crop yield, because of the low yield potential of crops in our study under organic farming and also lower S requirements of cereals than oilseeds. This suggests the need of future research to determine the feasibility of gypsum and other amendments (such as granular elemental S) in preventing S deficiency in organic crops on soils extremely deficient in available S for optimum crop growth and yield. In our study, wood ash increased yield of barley in both experiments in 2010, and this may be due to the supply of P, S, or other nutrients to the crop, because it contains fairly high content of available P, S, K, Ca and Mg, but little or no N.

In 2009, there was no beneficial effect on seed yield and/or nutrient uptake of pea from any amendment in Experiment 1 (in fact, seed yield and nutrient uptake of pea decreased with increasing rate of alfalfa pellets in this experiment), and only from compost application in Experiment 2. This was most likely that pea can fix N from the atmospheric air for its own requirement [8, 31-33] and do not need any N (probably the most limiting nutrient in soil at these sites) from external sources. Thus, suggesting little or no increase in yield of pea from N-supplying organic amendments, especially when soil is adequately supplied with P, S, K, or other nutrients and legume is the main crop. When legumes are grown in the rotation, it is also possible that their crop residue after decomposition may also provide N benefit to subsequent crops for improving yield under organic farming [32,34]. In Experiment 1, we did not expect any dramatic reduction in seed yield of pea from alfalfa pellets application treatments compared to the control. The decrease in seed yield of pea with increasing rate of alfalfa pellets was most likely due to the increase in wild oat infestation as evidenced by the significant increase in seed yield of wild oat with increasing rate of alfalfa pellets (data not shown; seed yield of wild oat ranged from 122 to 317 kg·ha⁻¹).

Previous research has suggested yield on organic farms can be increased (also called out-yielding calculated as LER) by intercropping non-legume and legume annual crops together compared to as sole crops for cereal-legume [10,11]. Similarly, in our study, the LER values were greater than 1 in the cereal-pea intercrop treatments compared to the wheat, barley, or pea as sole crops in 2 of the 3 years. This indicates less land requirement for wheat- or barley-pea intercrop compared to

wheat, barley, or pea grown as sole crops to produce the same seed yield. This also suggests the importance of growing intercrops in improving productivity and use efficiency of land and soil nutrients, while sustaining high crop production.

5. Conclusion

There was some potential benefit in improving yield and nutrient uptake of wheat and barley from compost, alfalfa pellets and possibly wood ash, and from intercropping non-legume wheat or barley with legume pea. Our findings suggest the need for future research to determine the feasibility of rock phosphate, *Penicillium bilaiae*, Myke-Pro, gypsum or other amendments in preventing P and/or S deficiency in organic crops using soils extremely deficient in these nutrients.

6. Acknowledgements

The author thanks Western Alfalfa for financial assistance and supplying alfalfa pellets amendment for this study, International Compost Ltd., Calgary, Alberta, for supplying Rock Phosphate fertilizers for this study, and D. Leach and K. Strukoff for technical help.

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