Can Slow-Release Monoammonium Phosphate and Struvite Improve Phosphorus Use Efficiency and Reduce Seedling Toxicity in Canola?

FINAL REPORT

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EXECUTIVE SUMMARY

Background

The management of large volumes of hog manure on agricultural land is a critical challenge due to its low N:P ratio and stringent regulations based on soil test phosphorus (P) levels. One potential option to reduce the concentrations of P in hog manure is the recovery, prior to land application, of manure P as struvite, a highly concentrated and readily transported product that also contains the plant nutrients nitrogen (N) and magnesium (Mg). The recovered struvite has low solubility or slow release properties, which may result in greater crop uptake of P compared with conventional fertilizers. The slow-release properties of struvite may also allow seed-row placement of P at higher rates than feasible with conventional fertilizers for salt sensitive crops.

Procedures

These pot experiments evaluated the effectiveness of struvite recovered from liquid hog manure as a P source for canola grown in rotation with wheat. Two separate experiments were conducted: (i) a greenhouse bioassay to evaluate the effectiveness of struvite on dry matter yield, which is directly correlated with grain yield), P uptake from applied struvite, P uptake efficiency (PUE, which is the percentage of applied P taken up by the crop), and agronomic P use efficiency (AE, which is a measure of dry matter produced per unit P applied) of canola grown in rotation with spring wheat, and (ii) a growth room experiment to assess canola seedling toxicity following seed-row placement of struvite. Two low-P soils with contrasting texture [a dark grey Gleyed Regosolic sand from a farm near Roseisle, Manitoba, and an Orthic Black Chernozemic clay loam from a farm near Justice, Manitoba, were used in the study which compared struvite with monoammonium phosphate (MAP) and polymer-coated MAP (CMAP, which is a controlled-release form of MAP) at rates corresponding to 25 and 50 kg P_2O_5 ha^{-1}. The lower rate approximates the maximum above which canola seed toxicity usually becomes a problem when MAP is the P source.

In the greenhouse bioassay, two sequences of alternating crops of canola and spring wheat (one crop sequence of canola-wheat-canola and the other of wheat-canola-wheat) were grown and harvested at early flowering. The P sources were placed either with the seeds in a 2.5-cm wide seed-row or in a 2.5-cm wide sideband 2.5 cm below and beside the seed-row. In the growth chamber study, seedbed utilizations of 5.5% and 10.9% were also tested, but with P-sources placed only in the seed-row. Seedlings were counted daily over a 14-day period to assess toxicity effects.

Results

Canola Biomass Yield and Phosphorus Uptake

Results from the greenhouse bioassay indicated significant responses of canola dry matter yield to all P sources relative to checks that did not receive P application, but only in the first crop in the rotation. In both soils, struvite produced canola dry matter yields comparable to MAP and CMAP in the first crop. By comparison, at the high P rate (50 kg P_2O_5 ha^{-1}), struvite out-yielded MAP in the second crop and both MAP and CMAP in the third crop. However, differences in yield between struvite and the MAPs at the low P rate were small. Across soils and placement methods, doubling the rate of struvite and MAP from 25 kg P_2O_5 ha^{-1} to 50 kg P_2O_5 ha^{-1} improved canola dry matter yield, whereas CMAP rate did not have a significant effect on the yield.

Seed-row placement produced significantly greater canola dry matter yield than side-banding in the first crop, but there were no significant differences in subsequent crop phases.

Overall, canola dry matter yield significantly declined with subsequent phases regardless of P source, indicating the progressive decrease in plant available P.

Over each entire crop cycle, plant uptake of applied P was similar for struvite, MAP and CMAP regardless of soil, placement method or rate. In both soils, canola recovered more P at the 50 kg P_2O_5 ha^{-1} rate than at the 25 kg P_2O_5 ha^{-1} rate in the first phase, regardless of placement method or P source. Overall, the higher P rate produced greater canola P uptake in the sand than in the clay loam. There were no significant differences in canola P-uptake between seed-row placement and side-banding regardless of P source.

In the first crop after applying P, canola recovered 46% of P applied to the sand compared to 40% recovery of P applied to the clay loam. Similar amounts of P were recovered from equivalent rates of the three P sources in both soils. On average, canola recovered a greater percentage of P applied at the lower (25 kg P_2O_5 ha^{-1}) rate (47%) compared with the 50 kg P_2O_5 ha^{-1} rate (39%) in the first crop.

Wheat Biomass Yield and Phosphorus Uptake

Wheat dry matter yield was generally similar for struvite, MAP, and CMAP, regardless of soil type, placement method, P rate, or crop phase. On average, wheat dry matter yield was 13% greater at the 50 kg P_2O_5 ha^{-1} rate (1.7 g dry matter kg^{-1} soil) than at the 25 kg P_2O_5 ha^{-1} rate (1.5 g dry matter kg^{-1} soil). Overall, wheat dry matter yield did not vary significantly from one phase to another in the clay loam, but declined from the first to the second phase in the sand.

In the first crop after P application, wheat recovered less P, averaged across rates, soils, and placement methods, from struvite (4.1 g mg^{-1}) than from MAP (5.1 g mg^{-1}) and CMAP (4.9 g mg^{-1}). Phosphorus recovery from all P sources was significantly greater at the high P rate than at the low rate in the first crop. Wheat recovered similar percentages of P (averaged across crop phases, rates, soils, and placement methods) applied as struvite (8.9%), MAP (11.5%), and CMAP (12.4%). Also, no significant differences in P recovery were observed between P rates in either soil.

In the clay loam, more P (averaged over P rates and P sources) was recovered by the wheat-canola-wheat sequence (12.6 mg P kg^{-1}) than by the canola-wheat-canola crop sequence (10.4 mg P kg^{-1}). This was reversed in the sand, in which the wheat-canola-wheat sequence recovered more P (10.9 mg P kg^{-1}) than the canola-wheat-canola sequence (9.5 mg P kg^{-1}). Overall, 55% of applied P was recovered (averaged across P-sources, placement methods, P rates, and soils) in the canola-wheat-canola crop sequence compared with 38% in the wheat-canola-wheat sequence.

Seedling Toxicity

The higher rate of MAP reduced overall seedling emergence in the clay loam by over 50%. By comparison, the slow release P sources, struvite and CMAP, showed no significant evidence of seedling toxicity in either soil. The apparent toxicity of MAP is mainly due to its high solubility, which tends to increase salt concentrations in the fertilizer band much more rapidly than CMAP and struvite. Averaged across soils, SBUs, and rates, final emergence decreased in the order: struvite (88%) > CMAP (86%) > MAP (69%), indicating the superiority of struvite with respect to reducing toxicity.

Conclusions

Results from this study indicate great potential for hog manure-recovered struvite to be an effective P-source for both canola and wheat. We found evidence of beneficial residual effects of struvite in the second and third crop phases in which struvite produced greater canola dry matter yields than MAP and CMAP. Thus, struvite may be a viable alternative to the widely used MAP and can alleviate toxicity issues associated with seed-row placement while improving P use efficiency in canola-wheat rotations. Importantly, this study demonstrates that struvite can be safely applied at higher P rates than can be safely applied with MAP, an important value for those farmers with P-deficient soils. In addition to the agronomic benefits, recovery of struvite from hog manure could be a sustainable way of recycling P from livestock operations, which are coming under increasing regulatory pressure due to environmental concerns (i.e., water quality problems in streams and lakes).

BACKGROUND

There is increasing pressure on agricultural producers to adopt best management practices (BMPs) to mitigate the increasing threat of eutrophication of surface water bodies (Beaulieu, 2004). Eutrophication is mainly attributed to phosphorus (P) from sediments deposited in runoff from P-enriched agricultural soils receiving high rates of P fertilizers or manure (Daniel et al., 1998; Sharpley et al., 2003a). This is a common problem for lakes such as Lake Winnipeg, MB, which receive large amounts of runoff from agricultural fields. According to a survey by Statistics Canada (2011), 98% of farms in Canada have some form of surface water on them (seasonal wetlands, permanent wetlands or waterways), and most of these ultimately offload in large lakes. The problem of agricultural pollution is aggravated by a lack of adequate environmental management strategies on farms. More than 50% of farmers in Canada fail to implement BMPs due to economic pressures (Statistics Canada, 2013).

Intensive hog production in western Canada generates large volumes of manure daily, with annual production estimated at > 16 million metric tons (fresh wt.) as of 2006 (Hofmann, 2013). Manitoba, which has the third largest hog population (2.8 million) of all Canadian provinces (12.7 million total) as of January 2014 (Statistics Canada, 2014), accounts for about 20% of daily manure output from hogs in Canada. Manure from hog operations is typically applied to agricultural land as a source of nutrients for crops. In some jurisdictions, including Manitoba, manure is often applied based on crop N needs. However, because the N:P ratios of hog manures (2:1 - 4:1) are usually lower than crop uptake ratios (4:1 - 7:1) (Nelson and Janke, 2007), annual applications of manure to meet crop N requirements can result in excessive soil test P (STP) levels. The excess soil P from manure application limits the amount of hog manure that can be applied on agricultural land without risking noncompliance with increasingly stringent regulations. Finding suitable land proximal to hog operations can be a daunting task, particularly where soils have received repeated applications of manure. This would necessitate transfer of manure to and its application on low P agricultural lands. However, transportation of large volumes of manure over long distances is economically unviable. There is, therefore, a need for alternative, more viable manure management options.

A promising alternative is the recovery of manure P as struvite [magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4 \cdot 6H_2O$)] prior to land application of manure. Since as early as 1858, waste-recovered P has been proposed for crops (Barak and Stafford, 2006). These proposals may have gone mostly unheeded in the agricultural sector due to the relative abundance and affordability of conventional P fertilizers. However, recently there has been increasing awareness on the potential benefits of using controlled- or slow-release fertilizers (SRFs) to minimize environmental hazards and to improve and maintain nutrient use efficiency (Shaviv and Mikkelsen, 1993).

The more gradual release of nutrients from struvite compared with conventional fertilizers qualifies it as a SRF (Shaviv, 2001a; Shaviv and Mikkelsen, 1993; Shaviv et al., 2003; Trenkel, 1997). The higher N:P ratio of manure following recovery of struvite allows the processed manure to be applied at rates that meet both N and P crop needs with minimal risk of excessive P build-up in the receiving soil, while the recovered struvite can be more economically transported for application on distant, low-P soils.

More than 75% of Canadian farmers rely on commercial fertilizers for profitable crop production (Statistics Canada, 2012). Monoammonium phosphate is the most commonly used P fertilizer on the Canadian prairies. In the 2011/2012 season, 2.9 million metric tonnes of MAP were shipped to the Canadian market, with 77% of this going to the prairies (Statistics Canada, 2012). Uncertainty over future supplies of P fertilizers, compounded by speculation that global phosphate rock deposits will be exhausted by 2050, is increasingly driving the search for alternative sources of P (Jasinski, 2006), such as struvite. However, there is a dearth of information on the agronomic performance of hog manure-derived struvite on high P-demand crops such as canola, which is also sensitive to high rates of seed row-placed soluble P fertilizers.

Seed row-placement is the most efficient method for placing P fertilizers under prairie conditions (Karamanos et al., 2002). However, despite the low salt toxicity index of MAP relative to other fertilizers (Rader et al., 1943), high rates in contact with seeds pose a risk of reduced germination and increased seedling mortality (Canola Council of Canada, 2011b; (Henry et al., 1995). Consequently, recommended rates for seedrow-placed MAP (22-28 kg P_2O_5 ha^{-1}) can only supply half the requirements of current high-yielding canola cultivars, which have a high P requirement (40-50 kg P_2O_5 ha^{-1}) (Grant and Bailey, 1993). To accommodate high rates, P fertilizers can be side-banded or broadcasted, but these placement methods require specialized equipment or reduce P use efficiency, respectively, relative to seed-placement.

The physical form of a fertilizer, its nutrient composition, and width of the fertilizer/seed band are critical factors influencing the safety (or toxicity) of fertilizers. Research has shown that when placed close to the seed, high rates of most fertilizers cause seedling toxicity (Qian et al., 2012). Moreover, liquid, powdery and fine textured fertilizers cause more damage than coarsely-granulated fertilizers as they tend to dissolve faster and rapidly increase salt concentrations in the band (Lombi et al., 2004). On the other hand, the width of fertilizer bands, the width of the row-space, and soil properties can influence the extent of damage from seed-placed fertilizers. The fraction of row width that is used by the fertilizer band [seedbed-utilization (SBU)] determines the influence of fertilizer salts on the solute potential of the soil solution (Roberts and Harapiak, 1997). Wide-spaced rows with narrow bands cause the most seedling damage, especially in dry soils.

Differences in fertilizer formulations and compositions cause some fertilizers to be less toxic than others, even when applied at the same rate. To date, it has not been established how different physical (powdery or granular) or chemical (purity and origin) forms and rates of struvite affect developing seedlings when placed in the seedrow. Specifically, there is a dearth of information on the agronomic performance of hog manure-derived 'low-purity' struvite on crops such as canola and spring wheat, which have a high P requirement. The overall objective of this study was, therefore, to evaluate the agronomic value of struvite recovered from liquid hog manure in canola and wheat production in P-deficient calcareous soils. Specific objectives were to compare the effects of differential rates of seedrow placed or side-banded struvite, MAP, and controlled-release monoammonium phosphate (CMAP) on: (i) canola plant stand; (ii) canola and wheat above-ground dry matter yield (DMY); and (iii) P use indices.

LITERATURE REVIEW

Pure struvite has a theoretical composition of 5.7% N, 12.6% P, and 9.9% Mg. Struvite can precipitate out of solutions containing the right proportions of Mg^{2+}, PO_4^-, and NH_4^+. Tremendous progress has been made in the struvite precipitation technology, with successful recovery of P (> 80% of reactive P) from dairy manure (Shen et al., 2010), human excreta (Gell et al., 2011; Jaffer et al., 2002), and swine manure (Ackerman and Cicek, 2011; Beal et al., 1999; Jordaan et al., 2010; Nelson et al., 2003; Quintana et al., 2005; Ryu and Lee, 2010). Due to its low solubility (Aage et al., 1997; Barak and Stafford, 2006; Doyle and Parsons, 2002; Nelson et al., 2003), hence slow-release nature, struvite could conceivably allow seed row placement of P at higher rates than currently feasible with conventional fertilizers such as MAP, without causing toxicity to canola seedlings.

The differences in physical and chemical form between struvite and MAP may be important for the rate of P supply to crops. However, the amount of readily-soluble P is more important in determining yields (Goh et al., 2013) . Goh et al. (2013) reported that short term differences in physical form, P solubility and availability of two ammonium orthophosphates (6 - 24 - 6 and 9 - 18 - 9), ammonium polyphosphate (10 - 34 - 0), and MAP (11 - 52 - 0) did not influence long-term solubility and P availability. Nonetheless, short term solubility is critical in determining seedling toxicity (Lombi et al., 2004) as it influences the osmotic potential gradient around seeds and developing seedlings.

Struvite has been shown to be an effective P fertilizer for corn (Barak and Stafford, 2006; Gell et al., 2011). When compared with monocalcium phosphate, it gave similar ryegrass DMY in sandy CLs with medium to high Olsen P concentrations (Johnston and Richards, 2003). In a greenhouse experiment using Italian ryegrass and corn, DMY and P uptake from struvites recovered from urine and manure equaled or exceeded those for Cederan phosphate fertilizer (Antonini et al., 2012). Plaza et al. (2007) also reported that struvite recovered from an anaerobic digester supernatant was as effective as single superphosphate at increasing DMY and supplying P to ryegrass. Similarly, wastewater-derived struvites gave similar spring wheat DMY to triple super phosphate fertilizer in slightly acidic (pH 6.5) and alkaline (pH 7.6) soils (Massey et al., 2009).

The salt toxicity index for MAP (29.9%) is relatively low, making it safer than most ammonium-based fertilizers (Rader et al., 1943). However, research has persistently shown that there is a risk of seedling toxicity associated with seed-placed MAP (Nyborg, 1961; Roberts and Harapiak, 1997). Some researchers suggest that the salt toxicity of MAP is less likely due to the generation of free ammonia (Moody et al., 1995) because there is negligible evolution of ammonia vapor from MAP (Allred and Ohlrogge, 1964). Hood and Ensminger (1964) concluded that detrimental effects of MAP on germinating cotton and wheat seeds were due to interference with enzymatic activity and not high levels of ammonium or phosphate ions. Monoammonium phosphate has also been found to induce severe Ca deficiency in developing seedlings in acid soils due to the precipitation of Ca in the fertilizer band (Moody et al., 1995), a mechanism which is of little consequence in the calcareous soils of western Canada. However, the salt index of struvite is unknown, and little is known about its safety or toxicity when applied at high rates close to or with seeds.

CROP GROWTH AND PHOSPHORUS UPTAKE STUDIES

MATERIALS AND METHODS

Hog Manure Recovered Struvite

The air-dry, finely-ground struvite was precipitated from anaerobically digested hog manure effluent with an optimal Mg:P ratio of 1.6:1 at pH 7.5 (Jordaan et al., 2010). For consistency of P source application, reverse osmosis (RO) water was added to moisten the struvite, forming a paste that was then dried and broken into uniform granules similar in size to MAP (11-52-0) granules.

Soils

The two soils (0- to 15-cm layer) used in this greenhouse bioassay were a dark-grey Gleyed Regosolic sand (Entisol) from Roseisle, MB (N 49° 33.577′; W 098° 24.824′) and an Orthic Black Chernozemic clay loam (CL) (Udic Boroll) from Justice (N 49° 58.590′; W 099° 52.908′), MB.

Laboratory Analyses

The hog manure-derived struvite was analyzed for total N using a Vario Max Elementar combustion analyzer (Elementar Analysensysteme GmbH, Donaustrasse, Germany). Ammonium N concentration was determined with a Timberline ammonium analyzer (Timberline Instruments, Boulder, Colorado) following extraction with 10 mL of 2 M KCl solution per gram of dry soil and 1 h shaking time (Mulvaney, 1996). Total P, K, Ca, and Mg in struvite extracts were determined by inductively coupled plasma - optical emission spectrometry (ICP-OES) with a Perkin Elmer 5400 (Perkin Elmer, Waltham, Massachusetts) following USEPA Method 3050B nitric acid/hydrogen peroxide/HCl digestion. Struvite pH was determined in a 1: 1 struvite: water suspension.

Plant available (Olsen) P was determined before initial planting and after each harvest using the ascorbic acid-molybdate method (Murphy and Riley, 1962) with a Skalar SAN++ segmented flow analyzer (Skalar Analytical B.V., Breda, Netherlands) following extraction with 0.5 M $NaHCO_3$ at a pH of 8.5 (Olsen et al., 1954). Nitrate N was determined by the Cd reduction method following extraction of 1 g soil in 10 mL of a 0.01 M KCl solution. Calcium and Mg were determined by ICP-OES (Perkin Elmer 5400, Perkin Elmer, Waltham, Massachusetts) following extraction of 5 g of soil with 33 mL ammonium acetate at pH 7. Particle size analysis was measured using the hydrometer method (Gee and Or, 2002). Electrical conductivity and pH were measured in a 1:1 soil to water solution. Soil organic matter content was determined using the loss on ignition method (Nelson and Sommers, 1996).

Total P in plant tissue was analyzed following digestion of 0.5 g of ground plant tissue with 10 mL concentrated HNO_3 using a MARS 5 microwave system (CEM Corporation, Matthews, NC). The temperature was ramped over 5 min from ambient to 175°C, at which it was held for an additional 15 min. After cooling, the digest was diluted to 100 mL with deionized water and analyzed with ICP - OES (Thermo iCAP 6300 Radial, Thermo Electron Corporation, Cambridge, UK).

Experiment Setup

The greenhouse bioassay was laid out in a randomized complete block design with a factorial combination of P source (struvite, MAP or CMAP), P rate (7.5 or 15 mg P kg^{-1}, which correspond to 25 and 50 kg P_2O_5 ha^{-1}, respectively), placement method (seed row or sideband), soil type (CL or sand), and three crop phases. Canola and wheat were alternately grown in two sequences (one sequence of canola-wheat-canola and the other of wheat-canola-wheat) to facilitate assessment of residual effects of fertilizer P. The canola-wheat rotation was chosen to reflect common practice on canola farms in the Canadian prairies. Unfertilized soils (controls) were included for comparison.

Soil Preparation and Planting

Field-moist soil was passed through a 4-mm sieve and thoroughly mixed before weighing 8 kg (dry wt.) into 12.5-L (23.5 cm L × 23.5 cm W × 23.5 cm H) plastic pots. Bulk densities after fertilizer application and packing were approximately 1.3 g cm^{-3} for the sand and 0.9 g cm^{-3} for the clay loam. Prior to seeding, all pots received 100-mL aliquots of a full-strength nutrient solution from which P was omitted (Zvomuya et al., 2006). Reverse osmosis water was added to bring soil moisture contents to 260 g kg^{-1} for the sand and 390 g kg^{-1} for the clay loam, which correspond to 65% and 61% water-filled pore space (WFPS), respectively. The pots were weighed and stored in the greenhouse for 24 h prior to planting.

Eight canola (cv. Invigor 5440) or 20 spring wheat (cv. A.C. Barrie) seeds were planted by hand at the 2-cm depth in 2.5-cm wide rows across the middle of each pot. Canola seeds were ~ 2.5 cm apart and wheat seeds were ~ 1.2 cm apart, giving target plant densities of 145 and 362 plants m^{-2}, respectively. Struvite (5.7-23-0.4), MAP (11-52-0) and CMAP (11-52-0) were applied to the potted soils at rates of 7.5 or 15 mg P kg^{-1} soil, which correspond to 25 and 50 kg P_2O_5 ha^{-1}, respectively. The 25 kg P_2O_5 ha^{-1} rate reflects the current recommended safe rate for seed-placed P for canola (22-28 kg P_2O_5 ha^{-1}) whereas the 50 kg P_2O_5 ha^{-1} rate reflects the P requirements for canola (Thomas, 2003). The fertilizers were placed either with the seed (seedrow placement) or 2.5 cm beside and below the seedrow (side-banding) in 2.5-cm wide bands across the center of each pot.

The weight of each pot after initial watering (to 65% WFPS for the sand and 61% WFPS for the clay loam) was noted and used as the basis for subsequent watering events. Throughout the study, the pots were weighed and watered with RO water at least once a week to replenish any moisture lost through evapotranspiration.

Harvesting

Plants were harvested at early flowering (39–43 d after emergence, DAE), which corresponded to BBCH stages 50 – 62 for canola (Lancashire et al., 1991) and Zadoks stages 39 – 57 for wheat (Zadoks et al., 1974). The plants were cut at approximately 2.5 cm above the soil surface using clippers. Harvested above-ground biomass from each pot was weighed after drying at 60°C for 48 h for dry mass determination. Dry samples were fine-ground (≤0.15 mm) prior to laboratory analysis.

After harvest, the soil in each pot was thoroughly mixed and a sample (~20-g dry wt.) taken, air-dried, and passed through a 2-mm sieve for laboratory analysis. Roots were chopped and mixed with the remaining soil. After re-potting the soil, 50 mL of a 0.6 M $CuSO_4{\cdot}5H_2O$ solution were added to each pot and thoroughly mixed with the soil. This was done to achieve a rate of 5 mg Cu kg^{-1} because signs of Cu deficiency were observed in the first wheat crop. Pots were reseeded with the alternate crop in the rotation. These procedures were repeated twice to give a total of three crops of canola and wheat, with 14-d fallow periods allowed between successive crops. After planting, soils were watered with a nutrient solution containing the remaining nutrients, except for P, at 50% of the concentration added at the first planting. Reverse osmosis water was added to correct the moisture content to the first crop levels.

Calculations

Phosphorus uptake (PU, mg P kg^{-1}) by plant shoots (aboveground biomass) in each pot was calculated as:

$$PU = DM \times P_{conc} \qquad [1]$$

where DM is the shoot dry matter yield (g kg^{-1} soil) and P_{conc} is the corresponding shoot P concentration (mg g^{-1}).

Fertilizer P uptake efficiency (PUE, %) was calculated as the difference in P uptake between fertilized (PU_{fert} g P kg^{-1}) and non-fertilized (PU_0, g P kg^{-1}) plants, expressed as a percentage of fertilizer P applied (P_{app}, g kg^{-1}):

$$PUE = \left(\frac{PU_{fert} - PU_0}{P_{app}}\right) \times 100 \qquad [2]$$

Agronomic efficiency (AE, g DM g^{-1} P), which is the amount of biomass produced per unit P applied, was calculated as:

$$AE = \left(\frac{DM_{fert} - DM_0}{P_{app}}\right) \qquad [3]$$

where DM_{fert} is the dry matter yield from fertilized pots and DM_0 is the dry matter yield from the control.

Cumulative PU was the total P uptake summed for all three crops in each of the two crop sequences, canola-wheat-canola and wheat-canola-wheat.

$$CumulativePU = PU_1 + PU_2 + PU_3 \qquad [4]$$

where PU_1, PU_2, and PU_3 are the PU values for the first, second, and third crops, respectively. A similar calculation was done for cumulative PUE.

Statistical Analyses

A repeated measures analysis of variance (ANOVA) was performed using the GLIMMIX procedure of SAS (SAS, 2011). Consistent with the factorial plus control design, the ANOVA was carried out in two steps: (i) comparison of fertilized treatments to the non-fertilized controls and (ii) comparison of fertilized treatments excluding the controls (factorial component). Soil, crop phase, P source, P rate, and placement method were fixed effects while block was the random effect in the model and crop phase was the repeated variable. Treatment effects were considered significant when $P < 0.05$. The Tukey-Kramer multiple comparison procedure was used to compare treatment means. Another ANOVA was performed on the cumulative P uptake and PUE, with crop sequence as a fixed effect in the model along with soil, P source, P rate, and placement method while block was a random effect.

Results

Recovered Struvite Properties

Recovered struvite had a pH of 5.5 and contained 10% elemental P and 5.7% TN (Table 1). X-ray diffraction analysis results performed previously indicated that all the Mg in the product was in the form of struvite (Jordaan et al., 2010). Therefore, calculations based on the Mg content suggested a maximum purity of approximately 65%, with a N:P:Mg ratio of 3.7:8.2:6.4 compared with 5.7:12.6:9.9 for pure struvite. About 81% of P in the recovered product was therefore in the form of struvite, with the remaining 19% as calcium phosphates or organic forms. The recovered struvite was in the form of a powder, and the hand-prepared granules were soft and crumbled easily after wetting.

Table 1. Selected chemical properties of hog manure recovered struvite and commercial fertilizers used in the greenhouse bioassay

†MAP is monoammonium phosphate (11-52-0) and CMAP is polymer-coated MAP

Analyte	Struvite	MAP	CMAP
	g kg^{-1} (air-dry basis)		
Total N	57.7	110	110
Ammonium N	16	110	110
Total P (P_2O_5)	230	520	520
K_2O	4.4	-	-
Ca	5	-	-
Mg	64	-	-
pH	5.5	4.8	4.8
Moisture (%)	40	1.2	1.2

Soil Properties

Selected properties of the soils used in the bioassay are shown in Table 2. Bicarbonate-extractable (Olsen) P concentrations of the clay loam (5.5 mg P kg^{-1} soil) and the sand (3.5 mg P kg^{-1}) were in the deficient range for canola and wheat. The clay loam had higher CEC, OM content, EC, field capacity moisture and, Ca and Mg contents.

Table 2. Selected chemical and physical properties of soils used in the experiments

Nutrient/Parameter	Sand	Clay loam
Nitrate (kg ha^{-1})	5.9	26.5
Olsen P (mg kg^{-1})	3.5	5.5
Mg (mg kg^{-1})	192	907
Ca (mg kg^{-1})	2348	3823
OM (%)	1.6	5.8
EC (S m^{-1})	0.02	0.04
pH	7.95	7.6
CEC (cmol$_c$ kg^{-1})	13.6	27.3
Field capacity moisture (kg kg^{-1})	0.1	0.3

Dry Matter Yield

Canola

In the first crop after P application, there were significant DMY responses to P fertilization in both soils ($P < 0.001$). In the second crop phase, all struvite treatments, seed-placed MAP and CMAP at 15 mg P kg^{-1}, MAP side-banded at 15 mg P kg^{-1}, and CMAP side-banded at 7.5 mg P kg^{-1}, produced significant responses in the clay loam. In the third crop, significant responses to seed-placed and side-banded struvite and seed-placed MAP and CMAP were attained in the clay loam at the 15 mg P kg^{-1} rate. In contrast, there were no significant canola DMY responses to P application in the sand in crop phases 2 and 3.

Results from the factorial component of the ANOVA (excluding the controls) showed a significant P source × crop phase interaction ($P = 0.004$) (Table 3). While canola DMY did not differ significantly among P sources in the first crop phase, struvite significantly outperformed MAP in the second phase and both MAP and CMAP in the third phase with respect to DMY (Figure 1). Overall, DMY significantly declined with each subsequent phase for all P sources.

There was also a significant P source × rate interaction ($P = 0.04$) for canola DMY, averaged across all phases (Table 3). At the high P rate, struvite produced significantly greater canola DMY than MAP and CMAP, but there were no significant differences among the P sources at the 7.5 mg P kg^{-1} rate (Figure 3). There were significant increases in canola DMY when struvite and MAP were applied at the 15 mg P kg^{-1} rate compared with the 7.5 mg P kg^{-1} rate, but the rate effect was not significant for CMAP.

The effect of P rate on canola DMY varied with soil and crop phase, as indicated by the significant ($P = 0.001$) rate × soil × crop phase effect (Table 3). Averaged across P sources, canola DMY in the third phase was significantly greater for the 15 mg P kg^{-1} rate than for the 7.5

mg P kg^{-1} rate in the clay loam (Fig. 3). By comparison, there were no significant differences between P rates in the first and second phases in the clay loam, and in all phases in the sand.

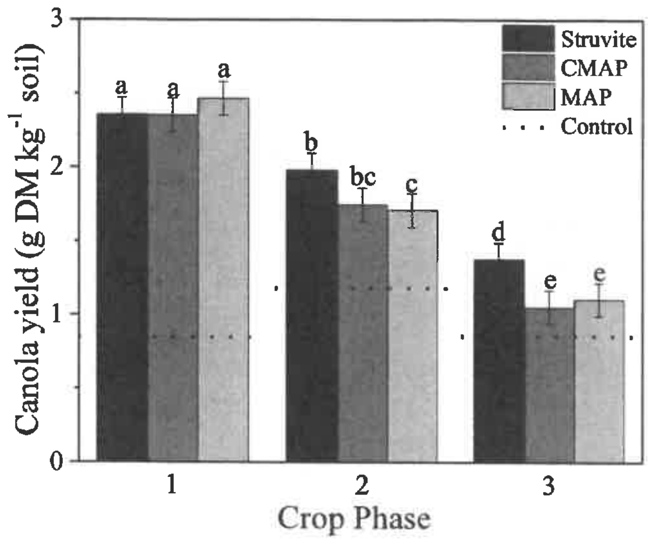

Figure 1. Canola dry matter yield as affected by P sources in the three crop phases. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure (P > 0.05). Error bars represent standard errors of the least squares means.

Placement method effects varied significantly with crop phase (P = 0.001). In the first phase, seedrow placement produced significantly greater DMY than side-banding, but no differences were observed in the second and third phases.

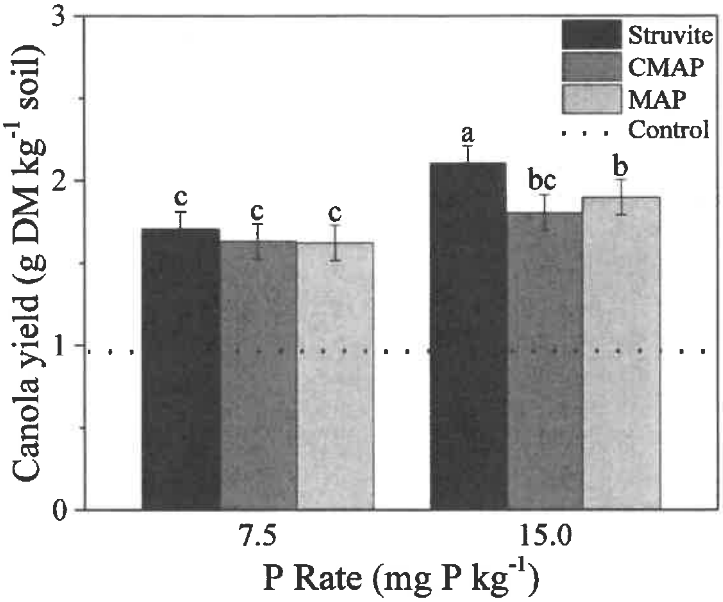

Figure 2. Effects of P source and rate on canola dry matter yield. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

Table 3. Canola and wheat dry matter yield (DMY), phosphorus uptake, and phosphorus efficiency (PUE), and agronomic efficiency (AE) as affected by struvite, MAP and CMAP application

Effect	DMY		P uptake		PUE		AE	
	Canola	Wheat	Canola	Wheat	Canola	Wheat	Canola	Wheat
	g kg^{-1}		mg kg^{-1}		%		g tissue mg^{-1} P	
Crop Phase (C)								
1	2.39	1.87	5.92	4.69	42.8	16.9	0.15	0.06
2	1.81	1.46	3.56	2.97	13.4	8.3	0.06	0.01
3	1.18	1.43	1.91	2.74	4.3	7.6	0.03	0.03
P source (P)								
CMAP	1.72	1.59	3.66	3.61	19.7	12.4	0.07	0.03
MAP	1.76	1.62	3.77	3.55	20.0	11.5	0.08	0.04
Struvite	1.91	1.55	3.95	3.25	20.8	8.9	0.09	0.03
Rate (R)								
7.5	1.65	1.50	3.26	3.16	21.8	11.5	0.09	0.03
15	1.94	1.67	4.33	3.78	18.6	10.3	0.07	0.03
Placement (Ap)								
Seedrow	1.84	1.62	3.79	3.49	20.4	10.4	0.08	0.03
Sideband	1.75	1.56	3.80	3.45	20.0	11.4	0.08	0.03
Soil (S)								
Clay loam	1.77	1.84	3.64	4.10	23.3	11.2	0.10	0.03
Sand	1.82	1.33	3.95	2.84	17.0	10.6	0.06	0.03
				P-value				
C	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
P	< 0.001	0.35	0.15	0.07	0.62	0.08	0.01	0.16
R	< 0.001	< 0.001	< 0.001	< 0.001	0.002	0.33	< 0.001	0.62
Ap	0.01	0.15	0.87	0.74	0.72	0.40	0.19	0.61
S	0.12	< 0.001	0.01	< 0.001	< 0.001	0.66	< 0.001	0.29
P × C	0.004	0.61	0.38	0.01	0.25	0.17	0.003	0.96
Ap × C	0.001	0.13	0.81	0.73	0.65	0.46	0.001	0.22
R × C	0.03	0.86	< 0.001	0.02	0.001	0.54	< 0.001	0.049
S × C	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.002
R × Ap	0.18	0.36	0.94	0.21	0.79	0.26	0.77	0.84
P × S	0.07	0.50	0.14	0.58	0.01	0.56	0.53	0.92
R × S	0.01	1.00	0.37	0.06	0.52	0.10	0.55	1.00
P × Ap	0.63	0.15	0.81	0.68	0.87	0.81	0.68	0.18
Ap × S	0.41	0.54	0.85	0.29	0.97	0.78	0.80	0.32
P × R	0.04	0.70	0.52	0.84	1.00	0.61	0.48	0.47
R × S × C	0.001	0.61	0.01	0.67	0.67	0.01	0.03	0.39
P × S × C	0.24	0.01	0.69	0.45	0.42	0.73	0.69	0.29
P × R × C	0.75	0.69	0.79	0.60	0.40	0.81	0.24	0.94
P × Ap × C	0.73	0.88	0.91	0.96	0.86	0.96	0.66	0.94
R × Ap × C	0.61	0.70	0.82	0.80	0.82	0.74	0.82	0.27
Ap × S × C	0.63	0.15	0.72	0.35	0.85	0.41	0.52	0.49
P × R × S	0.25	0.73	0.90	0.93	0.17	0.88	0.30	0.66
P × Ap × S	0.97	0.63	0.98	0.37	0.88	0.30	0.56	0.70

R × Ap × S	0.15	0.33	0.66	0.69	0.35	0.94	0.61	0.84
P × R × Ap	0.22	0.69	0.69	0.50	0.62	0.39	0.56	0.97
P × R × Ap × C	0.91	0.74	0.93	0.64	0.70	0.95	0.97	0.99
P × R × S × C	0.40	0.87	0.87	0.41	0.53	0.85	0.88	0.92
P × Ap × S × C	0.41	0.62	0.36	0.93	0.75	1.00	0.65	0.93
R × Ap × S × C	0.64	0.83	0.78	0.63	0.92	0.97	0.35	0.97
P × R × Ap × S	0.86	0.83	0.89	0.86	0.99	0.95	0.64	0.83
P × R × Ap × S × C	0.88	0.83	0.93	0.94	0.99	0.99	0.78	0.91

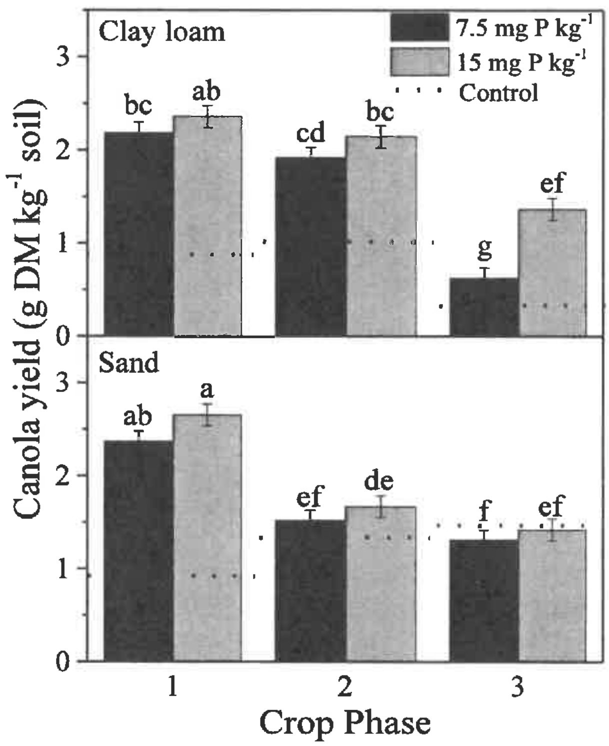

Figure 3. Changes in canola biomass yield over three crop phases as affected by P application rate. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure (P > 0.05). Error bars represent standard errors of the least squares means.

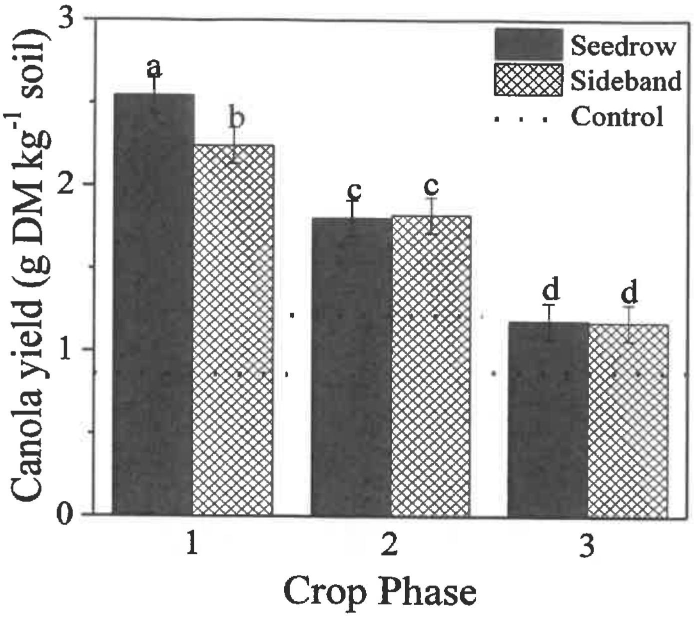

Figure 4. Effects of P placement on canola DMY over 3 crop phases. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

Wheat

In the first crop phase, the only significant wheat DMY response to P application was in the sand when MAP was applied in the seedrow at the 7.5 mg P kg^{-1} rate (2.3 vs 1.2 g kg^{-1} for the control). In all phases, there were no significant responses to any of the treatments in the clay loam.

Wheat DMY significantly varied with rate (Table 3). The 15 mg P kg^{-1} rate produced significantly greater wheat DMY (1.7 g kg^{-1}) than the 7.5 mg P kg^{-1} rate (1.5 g kg^{-1}), regardless of P source, placement, soil type, or crop phase. The effect of P source on DMY varied with soil and crop phase, as indicated by the significant soil × P source × crop phase interaction. In the sand, wheat DMY significantly decreased from Phase 1 to Phase 2, with no further significant decrease in Phase 3 (Figure 5). In contrast, no significant decrease in DMY was observed for any P source in the clay loam. In both soils, wheat DMY did not vary significantly among P sources in all phases.

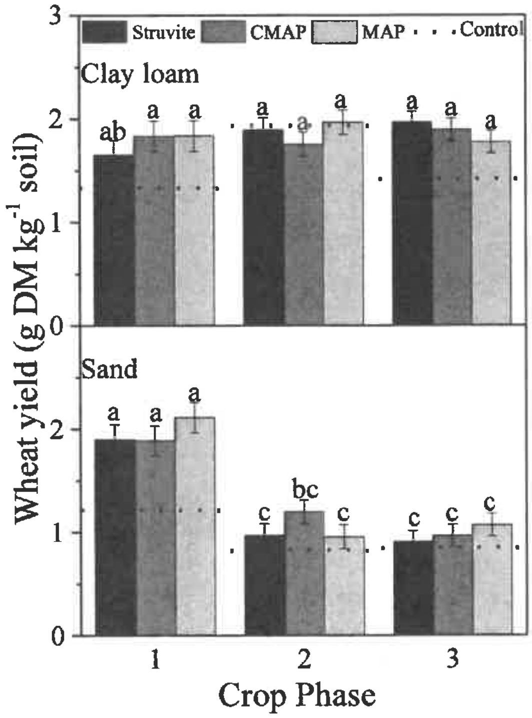

Figure 5. Wheat DMY as affected by P source and soil over 3 growth phases. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure (P > 0.05). Error bars represent standard errors of the least squares means.

Phosphorus Uptake

Canola

In the first phase, P uptake was significantly greater in P-fertilized soils than in the control. However, there were no further responses in P uptake to P application in the second and third crop phases. Analysis of variance of data excluding the controls showed a significant rate × soil × phase interaction on P uptake by canola (Table 3). Phosphorus uptake was greater at the 15 mg P kg^{-1} rate than at the 7.5 mg P kg^{-1} rate in the first phase in both soils. However, no significant differences were observed in subsequent phases (Figure 6). Also, no significant differences were observed among the P sources or between placement methods in both soils regardless of crop phase. Phosphorus uptake, averaged across P sources and placement methods, generally declined with subsequent canola phases at both rates, except for the 15 mg P kg^{-1} rate in the sand, which showed no decrease after the second phase.

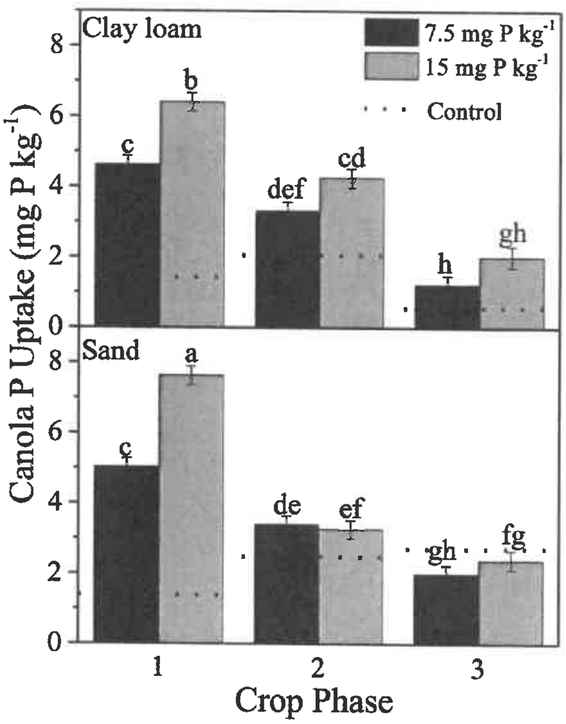

Figure 6. Effects of P rate and soil on canola P uptake over three crop phases. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure (P > 0.05). Error bars represent standard errors of the least squares means.

Wheat

In the first crop after P application, there was a significant increase in P uptake by wheat to MAP application at 15 mg P kg^{-1} in the sand (5.9 vs 1.8 g mg^{-1} for the control). However, no significant responses were observed for CMAP and struvite in this phase. Also, none of the treatments significantly increased wheat P uptake relative to the controls in the clay loam.

There were significant P source effects on wheat P uptake, which varied with phase, as indicated by the significant ($P = 0.01$) source × phase interaction (Table 3). In the first phase, P uptake by wheat was significantly lower with struvite (4.1 g mg^{-1}) application than with MAP (5.1 g mg^{-1}) or CMAP (4.9 g mg^{-1}) (Figure 7a). By comparison, P source differences were not significant in the second and third phases (Figure 7a).

There was a significant rate × phase interaction ($P = 0.02$) for P uptake (Table 3). In the first phase, P uptake from all P sources was significantly greater at the 15 mg P kg^{-1} rate than at the 7.5 mg P kg^{-1} rate (Figure 7b). There were no significant differences between the soils in all phases (Figure 7c). Wheat P uptake significantly declined in the second phase relative to the first phase, but there was no significant decline in the uptake in the third phase (Figure 7).

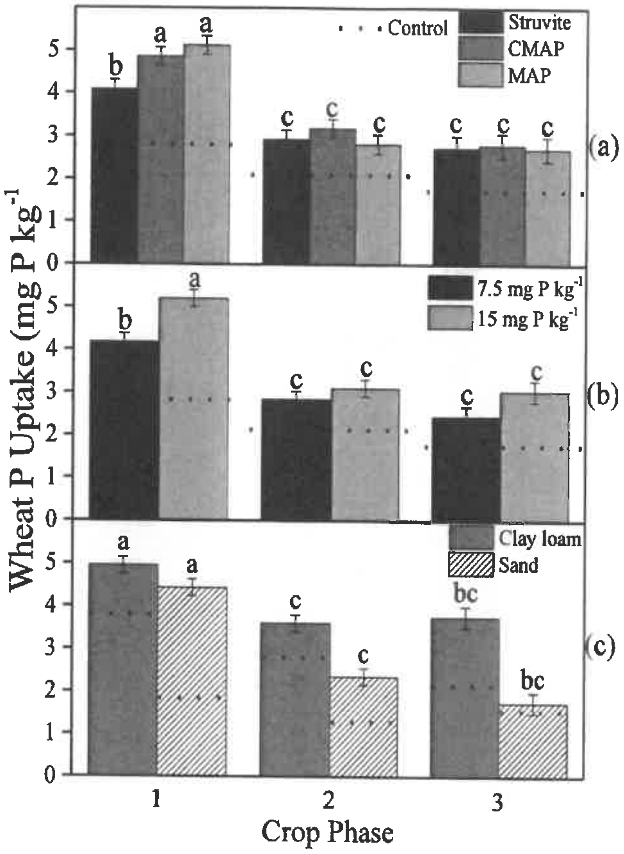

Figure 7. Effects of; (a) P source, (b) P rate, and (c) soil type on wheat P uptake over 3 growth phases. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

Phosphorus Use Efficiency Indices

Canola Phosphorus Uptake Efficiency

There was a significant P source × soil interaction ($P = 0.01$) for PUE averaged across phases. Struvite and CMAP produced significantly greater PUE in the clay loam than in the sand

(Figure 8). However, within each soil, the PUE was not significantly different among the P sources and ranged between 21% and 26% in the clay loam and 16% and 19% in the sand.

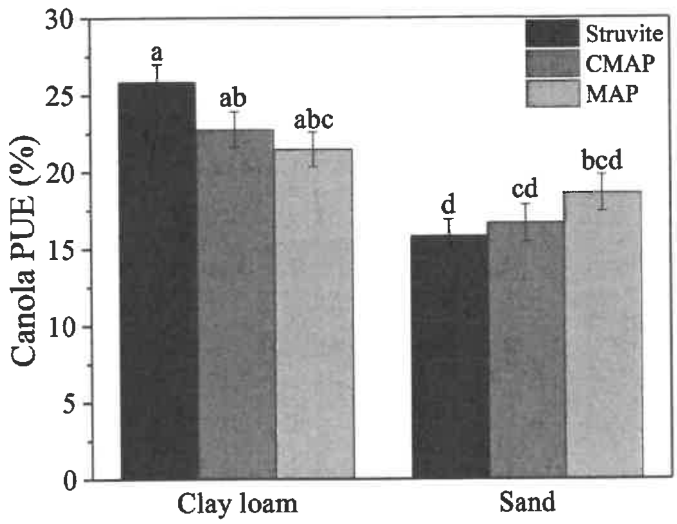

Figure 8. Phosphorus uptake efficiency of canola as affected by P source and soil type. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

There was also a significant rate × phase interaction ($P = 0.001$) (Table 3). In the first phase, the PUE, averaged across P sources, soils and placement methods, was significantly greater at the 7.5 mg P kg^{-1} rate (47%) than at the 15 mg P kg^{-1} rate (39%) (Figure 9). By comparison, no significant differences were detected between the rates in the second (mean PUE = 14%) and third (4%) phases.

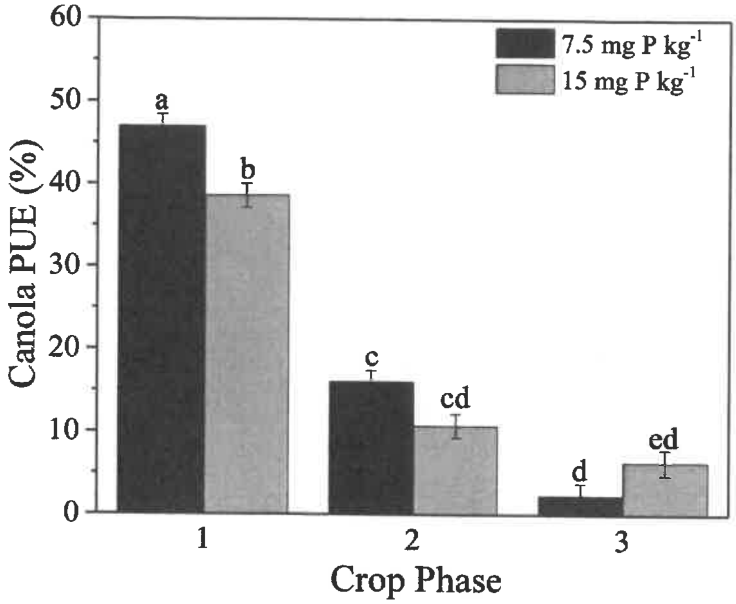

Figure 9. Phosphorus uptake efficiency of canola as affected by P rate and crop phase. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

There was a significant soil × phase effect ($P < 0.001$) for PUE (Table 3). The PUE of canola was significantly greater in the sand (46%) than in the clay loam (40%) in the first phase (Figure 10). In contrast, the opposite was observed in subsequent phases, with significantly greater PUE in the clay loam than in the sand (19% for the clay loam vs. 8% for the sand in Phase 2 and 12% vs. -3% for Phase 3).

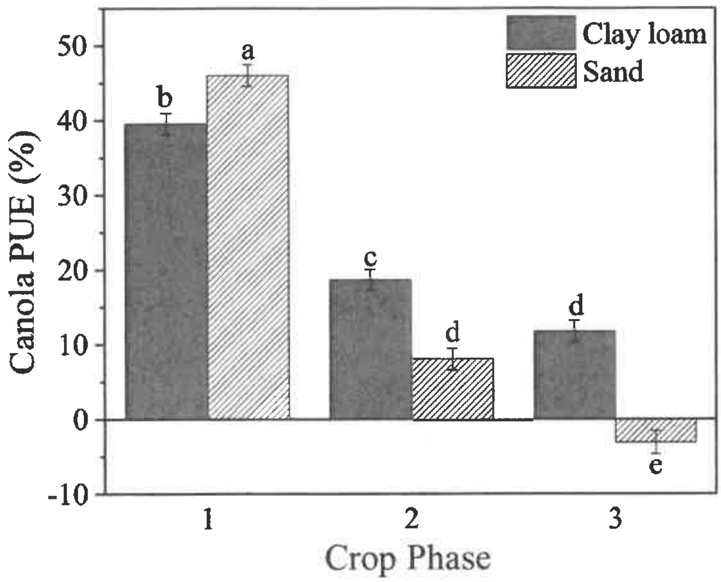

Figure 10. Phosphorus uptake efficiency of canola as affected by soil and crop phase. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

Wheat Phosphorus Uptake Efficiency

There was a significant rate × soil × phase interaction ($P = 0.01$) for PUE of wheat (Table 3). In the first phase, the PUE at the 7.5 mg kg $^{-1}$ rate was significantly greater in the sand (27%) than in the clay loam (9%) (Figure 11). By comparison, in the third phase, the PUE at the same rate was significantly lower in the sand (-6%) than in the clay loam (20%). Phosphorus uptake efficiency at both rates significantly declined from the first to the second phase in the sand, with no significant changes thereafter. However, at both rates, PUE in the clay loam did not vary significantly among phases. In both soils, PUE was not significantly different among the P sources, in all crop phases.

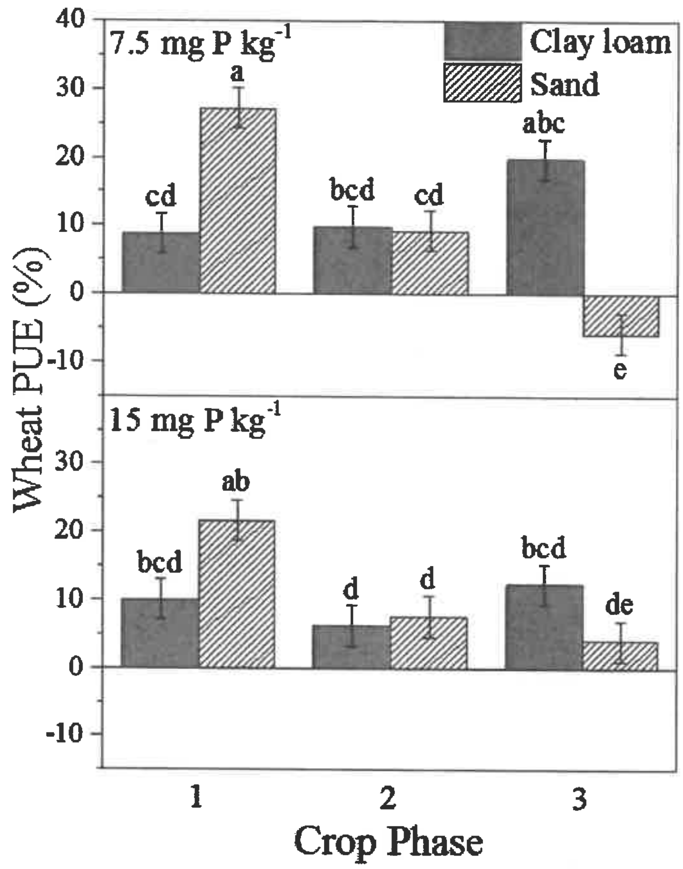

Figure 11. Wheat PUE as affected by soil, P rate, and crop phase. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

Canola Agronomic Phosphorus Use Efficiency

Phosphorus source effects on canola AE were significant but varied with phase, as indicated by the significant P source × phase interaction ($P = 0.003$) (Table 3). No significant differences were detected between struvite and MAP or CMAP in all three phases (Figure 12). For all P sources, AE significantly decreased from phase 1 to phase 2. However, only struvite and CMAP produced subsequently lower AE in the third phase, with no significant change in AE for MAP. There was a significant rate × soil × phase interaction (P = 0.03) (Table 3). In the clay loam, AE was significantly greater at the 7.5 mg P kg^{-1} rate than at the 15 mg P kg^{-1} rate in the first and second phases. In contrast, the 15 mg P kg^{-1} rate produced significantly greater AE than the 7.5 mg P kg^{-1} rate in the third phase. For the sand, the 7.5 mg P kg^{-1} rate produced significantly greater AE than at the 15 mg P kg^{-1} rate in the first phase, with no significant differences between the rates in subsequent phases (Figure 13).

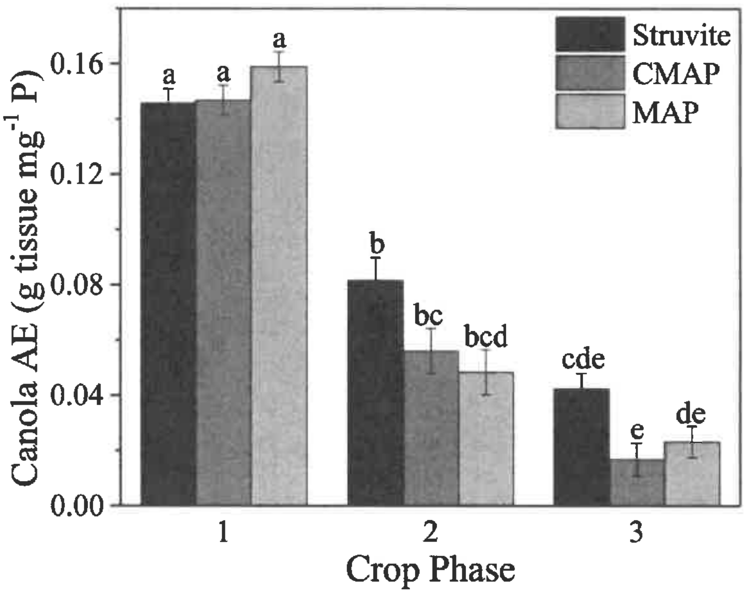

Figure 12. Phosphorus source and crop phase effects on canola AE. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure (P > 0.05). Error bars represent standard errors of the least squares means.

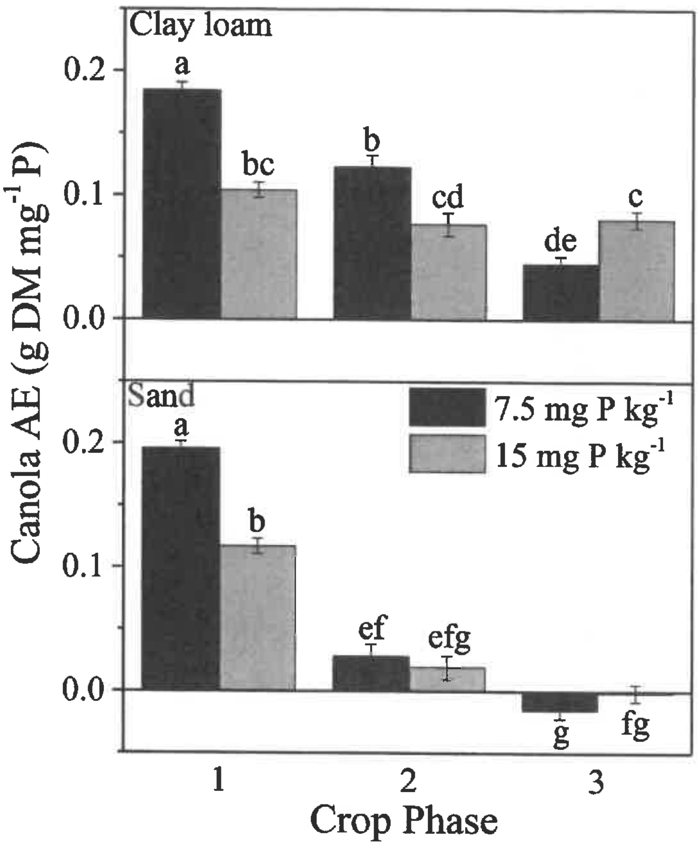

Figure 13. Effects of P rate, soil, and crop phase on canola AE. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

There was also a significant placement × phase interaction ($P = 0.001$) for AE (Table 3). Seed-row placement produced significantly greater AE than side-banding in the first phase (Figure 14). However, there were no significant differences between the placement methods in the second and third phases. For both placement methods, AE decreased significantly with subsequent phases.

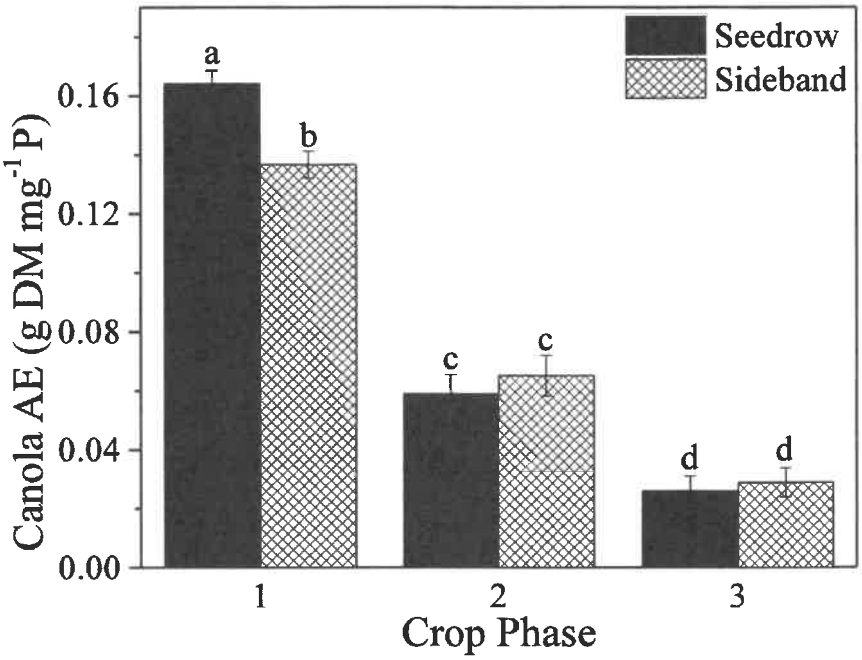

Figure 14. Phosphorus placement and crop phase effects on canola AE. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

Wheat Agronomic Phosphorus Use Efficiency

There was a significant rate × phase effect on wheat AE ($P = 0.049$) (Table 3). The 7.5 mg P kg^{-1} rate produced significantly greater AE (0.07 g DM mg^{-1} P) than the 15 mg P kg^{-1} rate (0.05 g DM mg^{-1} P) in the first phase, but there were no significant differences between rates in subsequent phases, which produced significantly lower AE values (0.004–0.03 g DM mg^{-1} P) than the first phase (Figure 15).

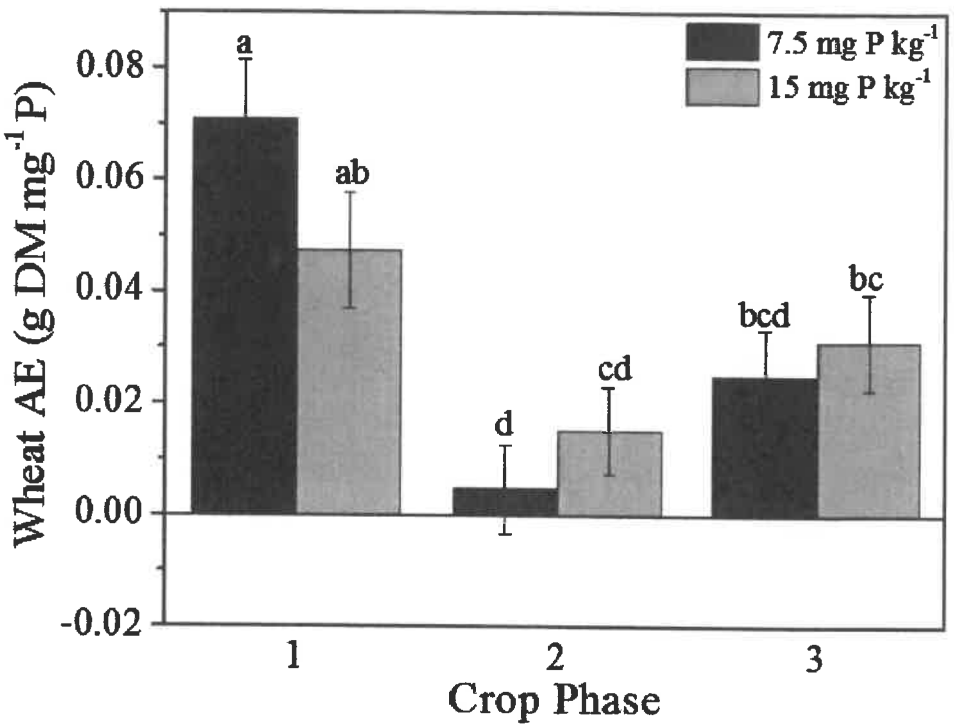

Figure 15. Phosphorus rate effects on wheat AE over 3 growth phases. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

There was also a significant soil × phase interaction ($P = 0.002$), although mean comparison did not indicate any significant differences between the soils in all phases (Figure 16). In both soils, AE was significantly lower in phase 2 than in phase 1. However, AE in the clay loam was significantly greater in phase 3 than in phase 2, but no significant difference between the two phases was observed in the sand.

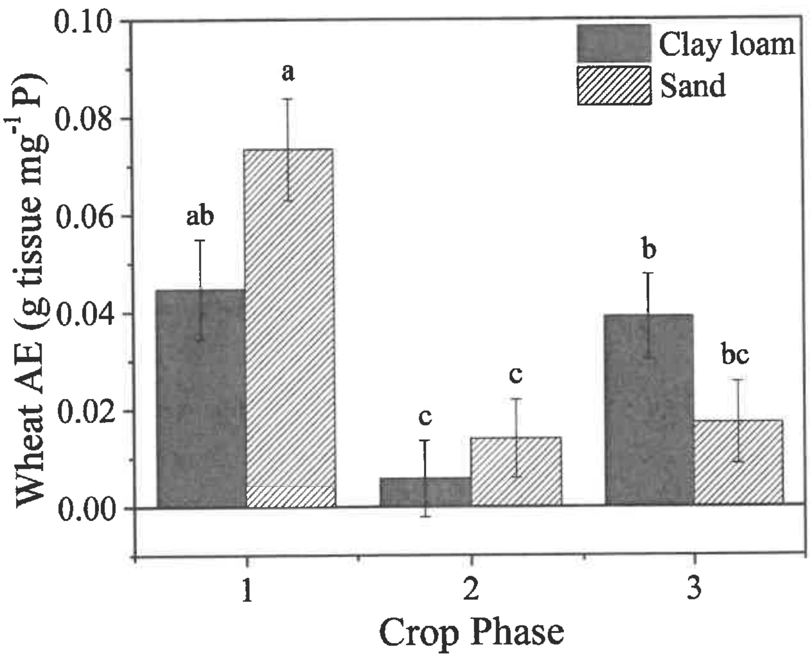

Figure 16. Wheat AE as influenced by soil type and crop phase. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

Crop Sequence Effects on Cumulative Phosphorus Uptake and Phosphorus Uptake Efficiency

There was a significant rate effect on cumulative P uptake, averaged over crop sequences ($P < 0.001$) (Table 4). Cumulative P uptake was greater at the 15 mg P kg^{-1} rate (12.1 mg P kg^{-1}) than at the 7.5 mg P kg^{-1} rate (9.6 mg P kg^{-1}). Phosphorus uptake was significantly affected by the starting crop in the rotation, but the differences varied with soil ($P < 0.001$ for the rotation × soil interaction). Phosphorus uptake when canola was the starting crop in the clay loam was significantly lower than when wheat was the first crop. The trend was reversed in the sand (Figure 17).

Table 4. Cumulative P uptake (PU) and P uptake efficiency (PUE) as affected by crop sequence, P source, P rate, application method and soil.

Effect	Cumulative PU	Cumulative PUE
	mg P kg^{-1}	%
Crop sequence (Cs)		
canola-wheat-canola	10.68	54.48
wheat-canola-wheat	11.02	37.91
P source (P)		
CMAP	10.90	46.93
MAP	10.88	47.10
Struvite	10.78	44.56
Rate (R)		
7.5	9.63	49.76
15	12.08	42.63
Application method (Ap)		
Seed-row	10.94	45.88
Sideband	10.77	46.51
Soil (S)		
Clay loam	11.50	51.07
Sand	10.20	41.32
	P-value	
P	0.92	0.58
Ap	0.51	0.78
Cs	0.19	< 0.001
R	< 0.001	0.002
S	< 0.001	< 0.001
P × Ap	0.97	0.96
P × R	0.88	0.51
P × S	0.06	0.02
Ap × S	0.21	0.86
Cs × P	0.65	0.92
Cs × Ap	0.58	0.91
Cs × R	0.16	0.70
Cs × S	< 0.001	0.22
R × Ap	0.12	0.30
R × S	0.15	0.30
P × Ap × S	0.71	0.85
P × R × Ap	0.72	0.44
P × R × S	0.85	0.63
Cs × P × Ap	0.64	0.70
Cs × P × R	0.54	0.47
Cs × P × S	0.99	0.96
Cs × Ap × S	0.60	0.22

Cs × R × Ap	0.59	0.99
Cs × R × S	0.18	0.45
R × Ap × S	0.37	0.71
P × R × Ap × S	0.42	0.60
Cs × P × Ap × S	0.24	0.13
Cs × P × R × Ap	0.23	0.21
Cs × P × R × S	0.25	0.18
Cs × R × Ap × S	0.62	0.65
Cs × P × R × Ap × S	0.63	0.98

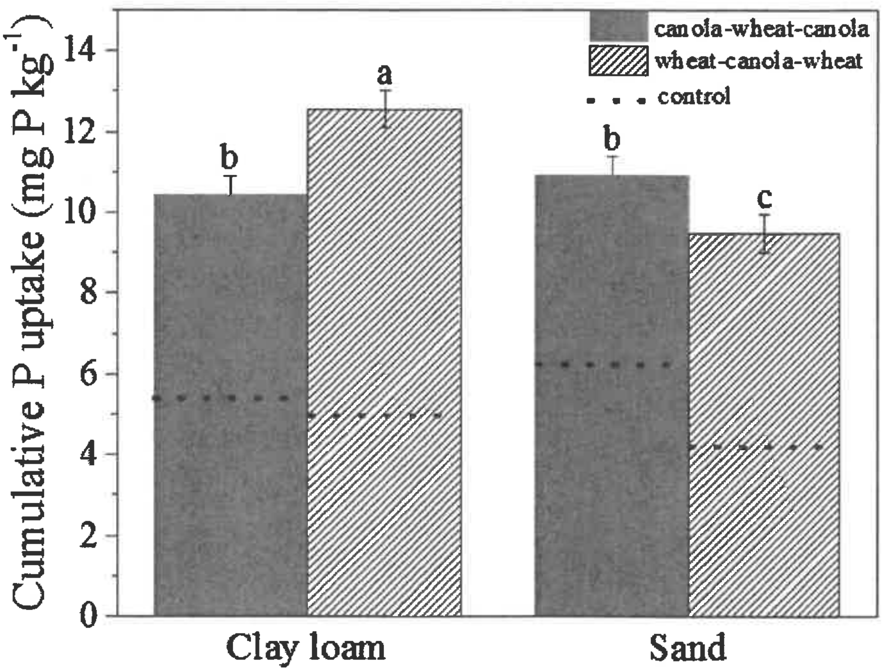

Figure 17. Effects of soil texture on the cumulative P uptake of three crop phases of canola-wheat-canola (CWC) or wheat-canola-wheat (WCW). Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure (P > 0.05). Error bars represent standard errors of the least squares means.

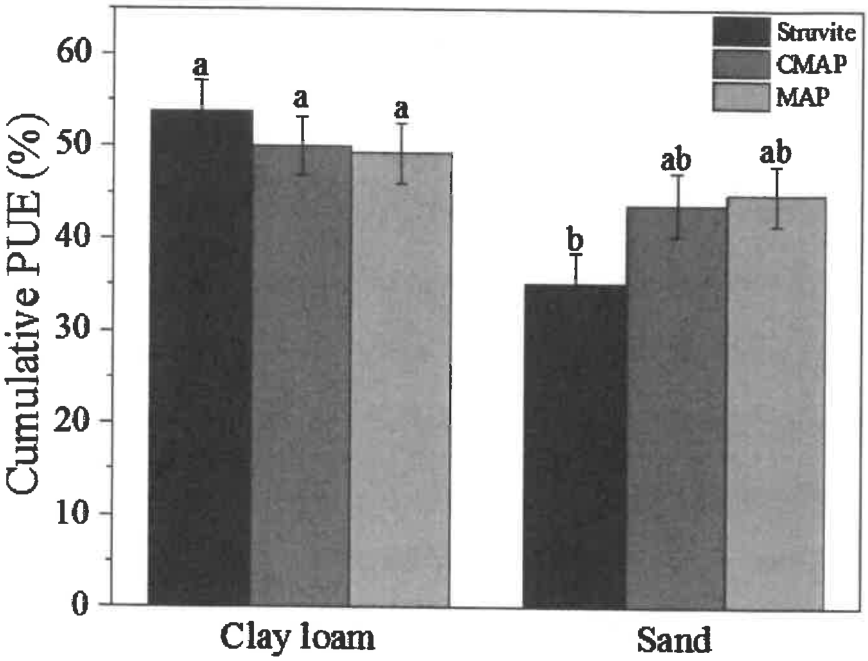

Figure 18. Cumulative P uptake efficiency for 3 phases of canola-wheat crop sequences as affected by P source and soil. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

Overall, PUE was significantly greater for the canola-wheat-canola crop sequence (overall PUE = 55%) than for the wheat-canola-wheat sequence (overall PUE = 38%) (Table 4). Struvite produced greater PUE at the 7.5 mg P kg^{-1} rate (35%) than at the 15 mg P kg^{-1} rate (54%), but there were no significant P rate effects for MAP and CMAP (Figure 18).

Bicarbonate-Extractable Phosphorus

In the clay loam, soil test (Olsen) P concentrations after harvesting (residual P) the first canola crop were significantly greater than the control (4.7 mg kg^{-1}) only when the 15 mg P kg-1 of MAP was applied regardless of placement method (7.3 mg kg^{-1}), and when the 15 mg P kg^{-1} of struvite was side-banded (7.1 mg kg^{-1}). Soil test P concentrations in all other treatments were not significantly different from the control. In the sand, only the 15 mg P kg^{-1} rate of MAP gave significantly greater residual P after the first (4.9 mg kg^{-1} vs. 2.7 for the control) and second (3.8 mg kg^{-1} vs. 1.9 mg kg^{-1}) phases of canola. No treatment significantly increased residual P after the third phase relative to the control.

After wheat harvest in the first phase, only the 15 mg P kg^{-1} rate of struvite produced significantly greater residual P (9.5 mg kg^{-1}) than the control (4.8 mg kg^{-1}) in the clay loam. No significant differences were observed in the clay loam between P-fertilized soils and the controls in the second (3.0 mg kg^{-1}) and third phases (2.4 mg kg^{-1}). Compared to the sand control in the first phase (1.9 mg kg^{-1}), only the 15 mg P kg^{-1} rate of MAP (regardless of placement) (5.3 mg kg^{-1}) and the seed-placed 15 mg P kg^{-1} rate of struvite (5.9 mg kg^{-1}) produced significant increases in residual P. However, no treatments were significantly different from the controls in the second (2.1 mg kg^{-1}) and third (1.7 mg kg^{-1}) phases.

Discussion

In spite of its low purity, the recovered struvite used in this study showed an overall agronomic performance that equaled or exceeded that of MAP and CMAP for canola production. For example, DMY, P uptake and PUE observed for canola in the first phase did not differ significantly among sources. The same comparable competitiveness of struvite was observed in both soils for wheat DMY, PUE, and AE in all phases. Although wheat P uptake from struvite was significantly lower than MAP and CMAP in the first phase, DMY was not significantly lowered. This was reflected by the similar AEs from the P sources, indicating that the differences between the amounts of P taken up were not large enough to translate into significantly lower yields. Moreover, in the clay loam, struvite produced greater canola DMY than MAP and both MAP and CMAP in the second and third phases, respectively. This indicates the ability of struvite to effectively supply P for longer durations than MAP and CMAP in this soil.

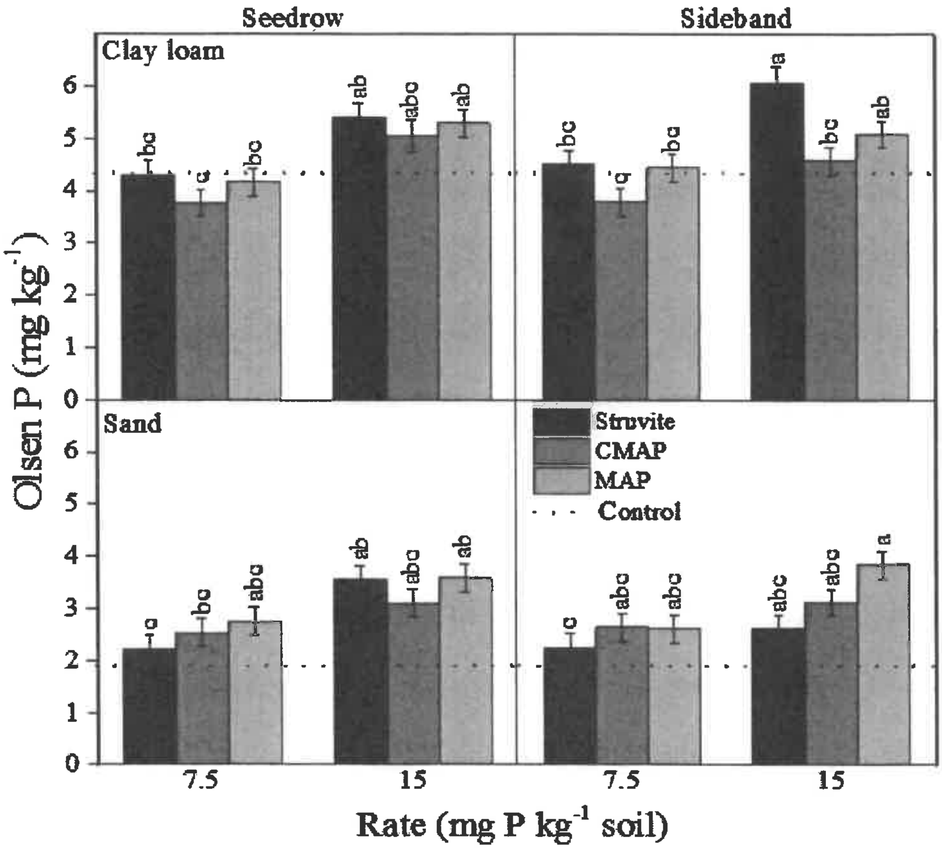

Figure 19. Residual soil P after harvesting wheat in the first phase. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of least squares means.

The P forms (struvite-P, Ca-P, and organic-P) in the recovered struvite have low solubilities, giving the product its slow-release properties. More than 80% of P in the recovered struvite was in the $MgNH_4PO_4{\cdot}6H_2O$ (struvite) form, which therefore largely determined the availability of P from the recovered stuvite. In pure water, the solubility of pure struvite at 25°C is in the range 160–200 mg L^{-1} (Aage et al., 1997; Barak and Stafford, 2006; Bhuiyan et al., 2007). The solubility decreases with increasing pH and decreasing temperature. Therefore, given the alkaline pHs of the clay loam (pH 7.6) and the sand (pH 7.95), and the temperature range (19-26°C) of this study, P release from struvite in the soil solution was generally expected to be very low (Barak and Stafford, 2006). The P in calcium phosphates and organic P forms (20%) was also potentially slowly available due to low solubility and high dependence on mineralization rates, respectively (Sharpley et al., 2003). Despite these factors, PUE of struvite was similar to that of MAP and CMAP for canola.

The long-term (that is, beyond the initial crop after P application) superiority of recovered struvite may be explained by the reduced exposure of P to soil fixing processes when it is gradually released. Release from MAP is very rapid, as indicated by its 85% water-solubility and 100% citrate-solubility (Chien et al., 2011). This is particularly important in a relatively high P-fixing soil such as the clam loam used in this study. Rapidly released P is quickly precipitated into forms that are not readily available (Ige et al., 2005). The greater uptake of P from struvite by canola, relative to wheat, may be due to the greater ability of canola to take up P (Föhse et al., 1991). This greater PUE of canola may have offset the low P release from struvite, leading to comparable P uptake for canola in the first phase.

The similar performance of struvite and the MAP fertilizers in the first canola crop after P application corroborates findings from numerous other studies which demonstrated various recovered struvite products to be of similar effectiveness to commercial P fertilizers for yields of corn (Barak and Stafford, 2006; Gell et al., 2011), ryegrass (Antonini et al., 2012; Johnston and Richards, 2003; Plaza et al., 2007), and spring wheat (Massey et al., 2009). In contrast, Ackerman et al. (2013) reported lower canola DMY and P uptake for hog manure recovered struvite compared with MAP and CMAP. However, unlike the P-deficient soils used in the present study, Ackerman et al. (2013) used a sandy loam of medium STP concentration (12 mg Olsen P kg^{-1}), which may explain the difference in results between their and the present study. It is likely that P-release from recovered struvite was more rapid in our P-deficient soils. The solubility of struvite depends on the speciation and concentrations of its ionic components (Mg^{2+}, NH_4^+, and PO_4^{3-}) in the soil solution (Bhuiyan et al., 2007). As soil STP increases, the PO_4^{3-} activity is expected to increase, further slowing down the dissolution of, hence release of P from, struvite.

Wheat showed no response to P application in all phases and produced high yields in the clay loam in the second and third crops. Not all wheat varieties respond to P application in most soils, regardless of STP (Korkmaz et al., 2009). In a P-deficient soil (8 mg Olsen P kg^{-1}), 10 out of the 15 wheat genotypes tested showed little or no response to 52 kg P ha^{-1}, which was broadcast and incorporated (Yaseen and Malhi, 2009). It is, therefore, highly likely that in these P-deficient soils, wheat acquired most of its P requirement from native soil P through mycorrhizal symbiosis without a need for additional fertilizer P. Canola has been reported to increase phosphatase activity and the abundance and diversity of P solubilizing soil microbes in the rhizosphere (Solaiman et al., 2007). This may have enhanced P supply for subsequent wheat crops, leading to the consistently high wheat yields in all phases.

Increasing P application rate from 7.5 to 15 mg P kg^{-1} significantly increased P uptake by both crops but did not significantly increase DMY and residual STP levels. However, the higher P rate produced greater tissue P concentrations at flowering (data not presented), which were within the recommended range (2.5 -5 g P kg^{-1}), whereas plants receiving the lower P rate had P concentrations indicating P deficiency (Grant and Bailey, 1993). Studies have shown that in soils with adequate P supply, sufficient P would have accumulated in canola tissue by early flowering (Malhi et al., 2006; Rose et al., 2008). The suboptimal P levels in canola tissue observed at the lower rate indicate that the 7.5 mg P kg^{-1} rate may not supply sufficient P throughout canola growth, although the observed early flowering biomass was similar to that for the 15 mg P kg^{-1} rate.

Seedrow placement of high rates of P fertilizers is known to pose greater risks of seedling injury than side-banding (Hocking et al., 2003; Nyborg, 1961), although it is the most efficient method of P application (Grant and Bailey, 1993). In this study, there was a significant reduction in seedling counts with seed-placed fertilizers (82% emergence) compared to side-banding (97% emergence) at the 15 mg kg^{-1} rate in the sand soil in the first phase (results not shown). Toxicity from seed-placed fertilizers is common under semi-arid conditions such as those in much of the Canadian prairies where precipitation is highly variable and moisture stress can aggravate seedling toxicity. In this study, soil moisture was maintained at close to optimal levels (61 – 65% WFPS), a scenario not very common in reality, which may explain the absence of significant injury from seed-placed fertilizers at the 7.5 mg P kg^{-1} rate in both soils and at the 15 mg P kg^{-1} rate in the clay loam.

The lack of a placement effect in the second and third phases was mainly due to the mixing of the soil prior to planting in these phases. Despite the observed reduction in canola seedling counts for the first phase in the sand with seed-placement (82%) relative to side-banding (97%), overall, DMY in this study did not appear to have been adversely affected by toxicity due to seed-row placement (Figure 4). In fact, canola DMY and AE in the first phase were significantly greater for seedrow placement than for side-banding. This is because canola biomass can compensate for low plant stands, while seed-placement improves accessibility of P during early seedling development (Grant and Bailey, 1993). Hocking et al. (2003) reported up to 40% reduction in canola DMY at flowering when P was applied at 26 kg P ha^{-1}, but the plants had recovered by physiological maturity.

The responses to P fertilization and treatment effects in the two contrasting soils were generally similar. However, the PUE of both canola and spring wheat in the first phase were significantly greater in the sand than in the clay loam. Based on baseline soil properties (**Error! Reference source not found.**), there may be greater short-term availability of P in the sand due to relatively lower P retention capacity compared with the clay loam. The CEC, clay content, OM concentration, and water holding capacity of a soil are important in influencing higher nutrient and moisture retention, important characteristics which influence spatial and temporal availability of immobile nutrients such as P. In alkaline Manitoba soils, soil clay content and Ca and Mg concentrations greatly influence P retention (Ige et al., 2005). High Ca and Mg concentrations indicate a high potential to precipitate P out of solution, making it less available for plant uptake. However, P availability has been linked to the long term release of P from precipitated phosphates that are formed when fertilizer P is fixed (Goh et al., 2013). Therefore, despite the high P-fixing potential of the clay loam, DMY and P-uptake in the two contrasting soils varied little among P sources.

Phosphorus uptake from the canola-wheat-canola crop sequence was nearly 20% greater than that from the wheat-canola-wheat sequence. Our results show that the PUE of canola (43%) was more than double that for wheat (17%) in the first crop after P application. This indicates the greater ability of canola to take up fertilizer P compared to wheat. Our results corroborate those from previous studies, which showed that canola required 50% less P than wheat because of its higher PUE (Bolland, 1997; Brennan and Bolland, 2001). Unlike wheat, canola does not form mycorrhizal symbiotic relationships or cluster roots (Shane and Lambers, 2005) to enhance P uptake from soil reserves. However, it has an efficient root-hair system and can exude carboxylates to acidify the rhizosphere (Pearse et al., 2006; Richardson et al., 2011), thereby enhancing its ability to take up available P. Thus, despite its high P demand relative to wheat, canola is more efficient in acquiring and utilizing fertilizer P to give higher DMY at low available P concentrations (Brennan and Bolland, 2009).

The hog manure recovered struvite (6-23-0.4) used in this study contained about half as much P and N as MAP and CMAP (11-52-0), consequently, twice as much struvite as MAP or CMAP was required to achieve the same P rate. The lower nutrient composition of struvite implies that higher transportation and application costs are likely to be incurred with struvite use than with MAP or CMAP. This however, would be of little consequence if the struvite is being sourced proximal to the land where the crop is being grown.

Conclusions

Overall, our results indicate that struvite was at least as effective as the commercial fertilizers, MAP and CMAP, in supplying P and supporting good canola and spring wheat biomass yields. Moreover, the residual benefits from struvite observed for canola in this study suggest a potential to improve the P status of P deficient soils. Improving the Olsen P levels of soils reduces the threshold amount of fertilizer P required to obtain optimal yields (McKenzie et al., 2003). Therefore, struvite is a potential alternative to relatively expensive controlled-release fertilizers, and its adoption within agricultural systems is a sustainable way of recycling P. In jurisdictions such as Manitoba, where stringent regulations on manure disposal are a critical challenge for hog producers, reducing manure P through struvite recovery can go a long way in easing the problem. Manure with lower P concentrations can be easily applied based on crop N demand without the risk of P overload. Also, crop producers can benefit from using struvite in place of conventional P fertilizers, especially where the soils are P deficient and high rates of P are required. In the long-term, the environmental and manure management benefits of struvite recovery and use show great potential to offset the additional production costs.

SEEDLING TOXICITY STUDIES

Methods and Materials

Experiment setup

The bioassay was laid out in a completely randomized design with a 2 × 3 × 2 × 2 factorial + 2 controls treatment structure and three replicates. The 4 factors were (i) soil (loamy sand and CL), (ii) P source (MAP, PCMAP, and struvite), (iii) P rate (7.5 and 15 mg P kg^{-1}), and (iv) seedbed utilization (SBU) (10.9% and 5.5 %). Five kilograms (dry wt.) of field-moist soil were weighed into 12.5-L (23.5 cm L × 23.5 cm W × 23.5 cm H) polyethylene pots and packed to bulk densities of ~1.0 g cm^{-3} for the clay loam and 1.3 g cm^{-3} for the sand. Two rows of canola were seeded 15 cm apart in each pot. Within each row, ten canola seeds were seeded 2 cm apart at a seeding depth of 2 cm. Phosphorus sources were applied at rates of 7.5 and 15 mg P kg^{-1} soil in 1.25- and 2.5-cm wide bands, representing SBUs of 10.9% and 5.5%, respectively. Immediately after seeding and P source application, all pots received full-strength nutrient solutions from which P was omitted (Zvomuya et al., 2006). Sufficient reverse-osmosis water was added to each pot to bring the moisture content to approximately 260 g kg^{-1} (65% water-filled pore space, WFPS) for the sand and 390 g kg^{-1} (61% WFPS) for the clay loam. Pots were checked every day after planting (DAP) and seedlings were counted until there was no change in seedling counts (16 DAP). The pots were weighed periodically and reverse-osmosis water was added as required to restore moisture content to the initial WFPS levels. Moisture depletion was not allowed to exceed 5% of the initial content (65 and 61% WPFS) before watering.

Statistical Analyses

Data was analyzed using the GLIMMIX procedure in SAS (SAS, 2011). A repeated measures ANOVA was performed on the cumulative emergence data, consistent with the factorial plus control design. The compound symmetry covariance structure was used based on the Akaike Information Criterion (AIC) (Akaike, 1974). The ANOVA was carried out in two steps: (i) comparison of fertilized treatments to the non-fertilized controls and (ii) comparison of fertilized treatments excluding the controls (factorial component). Soil, P source, P rate, SBU, and time (DAP) were fixed effects while the time effect was the repeated variable. Analysis of variance for the seedling counts at 16 DAP was also performed using the GLIMMIX procedure with soil, P source, P rate, and SBU as the fixed effects of the model.

Emergence from a batch of seeds is rarely synchronized as individual seeds may have different rates at which they break dormancy, resume metabolism, or tolerate stress (Bewley, 1997; Forcella et al., 2000) due to varying biophysical characteristics, and the microenvironment of soil surrounding each seed. Therefore, modelling emergence data provides more information from the dataset than when a simple analysis of a single parameter such as cumulative emergence or final seedling counts is done (Brown and Mayer, 1988a). Emergence data were fitted to several sigmoidal growth functions and the most suitable function was selected based on the criteria suggested by Brown and Mayer (1987), targeting practical relevance and simplicity (Torres and Frutos, 1990).

The Akaike Information Criterion (AIC) (Akaike, 1974) was used to evaluate the goodness of fit for each of the evaluated models, and the function with the lowest AIC values for the most treatments was selected as the one best describing canola cumulative emergence data. Of the models tested, the Richards, Morgan-Mercer-Flodin, and Weibull functions did not converge for some treatments and were therefore not considered further. The three functions that converged were:

(i) Mitscherlich: $E = M\left(1-\exp\left(-k\left(t-z\right)\right)\right)$, [5]

(ii) Logistic: $E = \dfrac{M}{\left(1+\exp\left(-kt+b\right)\right)}$, and [6]

(iii) Gompertz: $E = M\left(\exp\left(-\exp\left(-kt+b\right)\right)\right)$ [7]

where E is emergence at time t, t is time (DAP), M is the asymptotic (final) emergence percentage, k represents the emergence rate, and z and b, respectively, are directly and indirectly related to the lag (time to point of inflection) (Brown and Mayer, 1988b). The lag for the Logistic and Gompertz functions is calculated as:

$$\text{Lag} = \frac{b}{k} \qquad [8]$$

The Mitscherlich function had the highest AIC values, while the Logistic and Gompertz functions had lower and very similar AIC values for most treatments (Table 5). However, the Gompertz function had consistently lower values than the Logistic function for all treatments; therefore the Gompertz function was chosen to describe this data. Differences among treatments were determined using the approximate 95% confidence intervals obtained from the model fitting. For all parameters, treatments with overlapping confidence intervals were considered not significantly different (Motulsky and Christopoulos, 2004).

Table 5. The AIC results from fitting the Mitscherlich, Gompertz, and Logistic functions to canola emergence data, as affected by soil, P source, seedbed utilization (SBU), and P rate.

Treatment†	**Nonlinear Function AIC value**		
	Mitscherlich	**Gompertz**	**Logistic**
Clay loam			
Control	52.7	33.9	33.9
MAP-narrow-7.5	55.9	54.5	54.6
MAP-wide-7.5	52.8	49.1	49.3
MAP-narrow-15	54.9	54.2	54.2
MAP-wide-15	58.2	57.7	57.7
CMAP-narrow-7.5	52.7	42.8	42.9
CMAP-wide-7.5	52.6	41.6	41.6
CMAP-narrow-15	51.1	40.6	41.6
CMAP-wide-15	51.6	43.5	44.0
Struvite-narrow-7.5	56.0	54.9	55.1
Struvite-wide-7.5	53.4	50.4	50.7
Struvite-narrow-15	56.7	55.1	55.3
Struvite-wide-15	57.4	55.7	55.8
Sand			
Control	56.4	54.8	55.1
MAP-narrow-7.5	51.3	49.9	50.2
MAP-wide-7.5	54.3	53.2	53.5
MAP-narrow-15	55.5	54.5	54.7
MAP-wide-15	55.9	55.3	55.5
CMAP-narrow-7.5	56.4	55.7	55.9
CMAP-wide-7.5	57.3	56.7	56.9
CMAP-narrow-15	57.6	56.7	56.9
CMAP-wide-15	57.8	57.2	57.4
Struvite-narrow-7.5	53.4	50.4	50.8
Struvite-wide-7.5	52.5	50.0	50.3
Struvite-narrow-15	56.6	52.0	52.1
Struvite-wide-15	54.1	49.3	49.6

† Narrow and wide; 5.5% and 10.9% SBU, respectively; 7.5 and 15; P rate in mg P kg^{-1}

‡ AIC, Akaike Information Criterion

Results

Cumulative Time-Course and Extent of Seedling Emergence

Analysis of variance

Treatment effects on cumulative emergence and final counts were assessed relative to the control for each soil separately. Cumulative seedling emergence at 16 DAP was significantly reduced, relative to the control, by MAP application at the 15 mg kg^{-1} rate (54%) in the clay loam. By comparison, there was no significant decrease in seedling emergence due to any of the treatments in the sand.

The full factorial ANOVA, in which the controls were excluded, showed a significant source effect on cumulative emergence, which varied with rate and soil type, as indicated by the significant ($P = 0.01$) P source × rate × soil interaction (Table 6). This interaction was further explored using nonlinear regression analysis, as described below.

There was also a significant soil × DAP interaction, with significantly greater emergence in the clay loam than in the sand during the first 13 DAP but no significant soil effect thereafter (Table 7, Figure 20). Overall, there was no significant effect of SBU on cumulative emergence.

Final seedling counts in the controls were not significantly different between the sand (87%) and the clay loam (100%). In the clay loam, MAP applied at the 15 mg kg^{-1} rate significantly reduced final seedling counts to 60% and 48 % relative to the controls when applied at the 10.9% and 5.5% SBUs, respectively. In contrast, application at the 7.5 mg kg^{-1} rate (85%) did not significantly reduce the final counts in this soil regardless of SBU. Similarly, struvite (90%) and CMAP (97%) did not significantly reduce final counts, regardless of P rate and SBU. Conversely, no treatments significantly reduced final counts relative to the control in the sand.

The full factorial ANOVA showed a significant P source effect which varied with soil type and P application rate, as indicated by the significant soil × P source × rate interaction (P = 0.007) (Figure 21).

Table 6. Cumulative canola seedling counts as affected by P source, P rate, seedbed utilization (SBU), days after planting (DAP), and soil.

Effect†	Seedling counts‡
Soil (S)	
Clay loam	8.17
Sand	5.60
P source (P)	
CMAP	7.41
MAP	5.64
Struvite	7.59
P-rate (P)	
7.5 mg P kg^{-1}	7.05
15 mg P kg^{-1}	6.72
Seedbed utilization (SBU)	
5.5%	6.82
10.9%	6.04
	P-value
P	**0.01**
R	0.29
SBU	0.65
S	**0.02**
DAP	**< 0.001**
P × R	**0.004**
P × SBU	0.15
P × S	**0.002**
P × DAP	0.07
R × SBU	0.28
R × S	0.06
R × DAP	0.24
SBU × S	0.15
SBU × DAP	0.93
S × DAP	**< 0.001**
P × R × SBU	0.58
P × R × S	**0.01**
P × SBU × S	0.26
P × R × DAP	0.97

P × SBU × DAP	1.00
P × S × DAP	0.22
R × SBU × S	0.79
R × SBU × DAP	0.99
R × S × DAP	0.77
SBU × S × DAP	0.73
P × R × SBU × S	0.15
P × R × SBU × DAP	1.00
P × R × S × DAP	0.80
P × SBU × S × DAP	1.00
R × SBU × S × DAP	0.94
P × R × SBU × S × DAP	1.00

†Main effect least squares means are presented for all main effects except DAP, which is graphed in Figure 20

‡Emerged seedlings out of 10 seeds row^{-1}

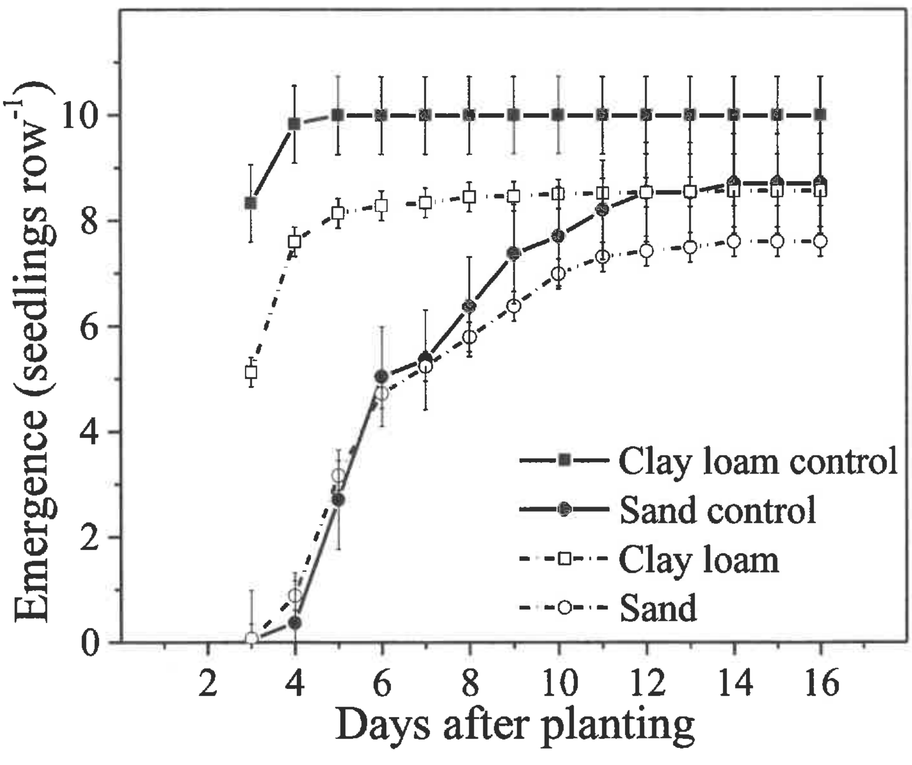

Figure 20. Cumulative emergence in a clay loam and sand soil over a 16-d study period. Error bars represent standard errors of the least squares means.

Table 7. Final seedling counts at 16 days after planting (DAP) as affected by P source, P rate, seedbed-utilization (SBU), and soil.

Effect	Seedling counts†
Soil (S)	
Clay loam	8.57
Sand	7.61
P source (P)	
CMAP	8.58
MAP	6.94
Struvite	8.75
Rate (R)	
7.5	8.35
15	7.83
Seedbed utilization (SBU)	
10.9%	8.21
5.5%	7.97
	P-value‡
S	< 0.0001
P	0.0005
R	0.30
SBU	0.55
S × P	0.0002
S × R	0.18
P × R	0.009
S × SBU	0.41
P × SBU	0.17
R × SBU	0.76
S × P × R	0.007
S × P × SBU	0.41
S × R × SBU	0.57
P × R × SBU	0.61
S × P × R × SBU	0.16

†Emerged seedlings out of 10 seeds row^{-1}

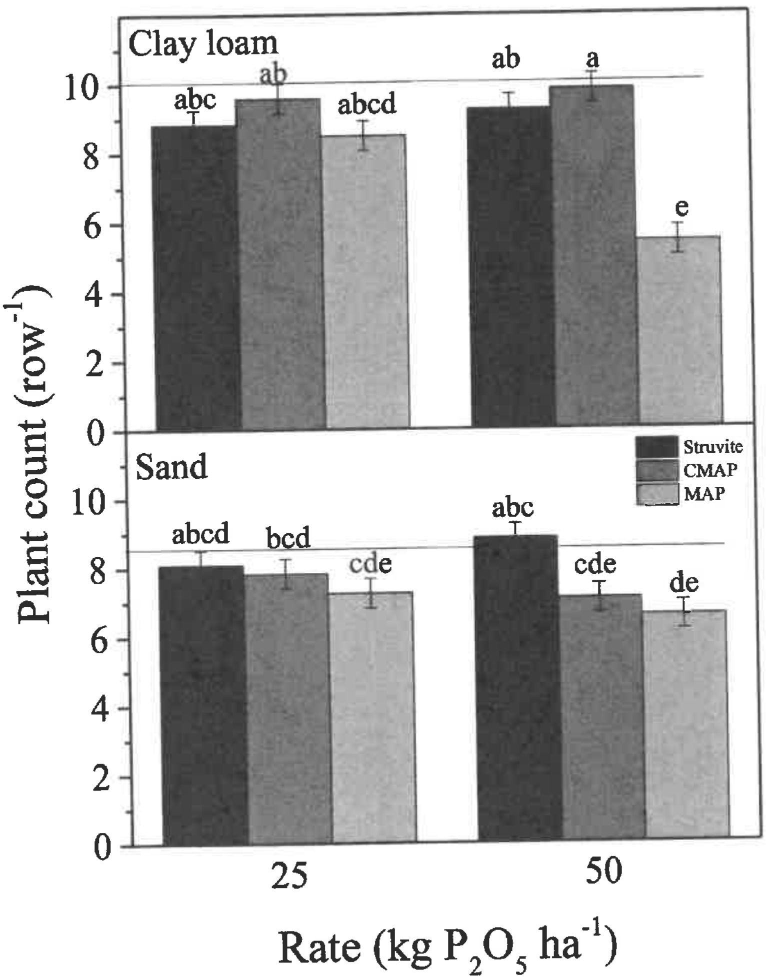

Figure 21. Effects of P source, rate, and soil on final seedling counts (out of 10 planted seeds). Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

Gompertz function

Final emergence percentage

Nonlinear regression analysis using the Gompertz function indicated that in the clay loam, there was a significant SBU effect at both rates of MAP, the 15 mg kg^{-1} rate of CMAP, and the 7.5 mg kg^{-1} rate of struvite (Table 8). All MAP treatments significantly reduced final emergence percentage by up to 52% relative to the control (100%) when the fertilizer was applied at the 15 mg P kg^{-1} at the 5.5 % SBU (emergence = 48.3%). The side-banded 7.5 mg kg^{-1} rate resulted in the smallest reduction (12%) for MAP.

Except for the narrow-banded (low SBU) 7.5 mg kg^{-1} rate (final count = 81%), all struvite treatments significantly reduced final seedling count by less than 10%. For CMAP treatments, application at the 7.5 mg kg^{-1} rate at either SBU, and at the 15 mg kg^{-1} at 11% SBU, significantly lowered final emergence by, at most, 5% (Table 8).

Coated MAP, when applied at 15 mg P kg^{-1} at an SBU of 5.5% did not significantly reduce final emergence (99.2 %) relative to the control. On the other hand, there were no significant differences in final seedling counts between the control (86.1%) and any of the struvite treatments in the sand (77 – 89%). Also, there were no significant struvite or CMAP rate and SBU effects on final seedling counts. Relative to the control, only the low SBU 15 mg P kg^{-1} of CMAP (66.5%) caused a significant (20%) decrease in final emergence percentage while the other CMAP treatments had no significant effect. For MAP, only the wide-banded 7.5 mg kg^{-1} rate (82.6%) did not significantly lower final emergence percentage and its emergence was significantly greater than for all other MAP treatments. The narrow-banded 7.5 mg kg^{-1} rate, narrow-banded 15 mg kg^{-1} rate, and wide-banded 15 mg kg^{-1} rate of MAP reduced final emergence percentage by 20, 22, and 18%, respectively.

Table 8. Phosphorus source, rate, and SBU effects on final canola seedling counts and Gompertz function parameters for cumulative percentage emergence data.

Treatment†	Emergence %‡	RMSE	*M*§	*k*	*b*	lag (*b/k*)
Clay loam						
Control	100.0	2.56	99.9 a	3. 5 a	8.7 a	2.5
MAP-narrow-7.5	81.7	14.31	79.8 d	1.7 ab	4.8 a	2.8
MAP-wide-7.5	88.3	9.11	87.5 c	1.9 ab	5.5 a	2.8
MAP-narrow-15	48.3	13.92	48.3 f	1.9 ab	5.5 a	3.0
MAP-wide-15	60.0	18.67	58.4 e	1.7 ab	5.2 a	3.0
CMAP-narrow-7.5	96.7	5.41	96.1 b	3.1 ab	7.8 a	2.5
CMAP-wide-7.5	95.0	4.89	94.9 b	3.3 ab	8.3 a	2.5
CMAP-narrow-15	100.0	4.51	99.2 a	2.1 ab	5.5 a	2.6
CMAP-wide-15	96.7	5.70	95.7 b	2.0 ab	5.3 a	2.7
Struvite-narrow-7.5	81.7	14.78	80.6 d	1.5 b	4.0 a	2.7
Struvite-wide-7.5	95.0	10.18	93.2 b	1.9 ab	4.9 a	2.6
Struvite-narrow-15	93.3	15.10	91.6 bc	1.8 ab	4.8 a	2.7
Struvite-wide-15	91.7	15.82	90.6 bc	2.0 ab	5.3 a	2.7
Sand						
Control	86.7	14.71	86.1 a	0.5 b	2.9 bc	5.2
MAP-narrow-7.5	80.0	9.79	65.9 b	0.4 b	2.6 bc	6.3
MAP-wide-7.5	65.0	12.80	82.6 a	0.4 b	2.5 c	5.6
MAP-narrow-15	66.7	14.30	64.1 b	0.6 b	3.1 abc	5.1
MAP-wide-15	65.0	15.32	67.8 b	0.4 b	2.3 bc	5.6
CMAP-narrow-7.5	81.7	15.78	80.9 ab	0.5 b	2.5 bc	4.9
CMAP-wide-7.5	75.0	17.18	75.5 ab	0.5 b	2.4 bc	5.2
CMAP-narrow-15	73.3	17.25	66.5 b	0.8 ab	3.6 abc	4.8
CMAP-wide-15	68.3	17.97	75.3 ab	0.4 b	2.4 bc	5.8
Struvite-narrow-7.5	85.0	10.17	84.0 a	0.6 b	3.1 bc	4.9
Struvite-wide-7.5	76.7	9.79	76.9 a	0.5 b	2.9 bc	5.3
Struvite-narrow-15	90.0	11.66	89.3 a	1.6 a	6.7 a	4.2
Struvite-wide-15	86.7	9.26	86.1 a	0.9 ab	4.2 ab	4.6

†Narrow and wide; 5.5% and 10.9% SBU, respectively; 7.5 and 15; P rate in mg P kg^{-1}

‡From ANOVA of final seedling emergence data (Table 7)

§Parameters M, k, and b represent final emergence (% of seeds planted), emergence rate (number of seedlings d^{-1}) and, indirectly, the lag in emergence (b/k) [days after planting (DAP)], respectively. Numbers in a column followed by the same letter are not significantly different according to the 95% confidence intervals.

Emergence rate

In the clay loam, struvite applied at the 7.5 mg kg^{-1} rate in a narrow band significantly reduced emergence rate (15% d^{-1}) relative to the control (35% d^{-1}). However, this treatment was not significantly different from all the other fertilized treatments in the clay loam, which had emergence rates ranging between 17 and 33% d^{-1} (Table 8). For the sand, the narrow-banded 15 mg kg^{-1} rate of struvite significantly improved emergence rate from 5% in the control to 16% d^{-1}. Conversely, there were no significant effects of the other treatments on emergence rate. The narrow-banded 15 mg kg^{-1} rate of struvite had a significantly faster rate of emergence (16% d^{-1}) than the narrow-banded (6% d^{-1}) and wide-banded (5% d^{-1}) 7.5 mg P kg^{-1}. However, there were no significant differences between the wide-banded 15 mg P kg^{-1} (9% d^{-1}) and the 7.5 mg P kg^{-1} (5%). The narrow-banded 15 mg P kg^{-1} of struvite produced a significantly greater emergence rate (16%) than that of MAP (6% d^{-1}), but both were not significantly different from that for CMAP (8% d^{-1}). However, there were no significant differences in emergence rate among all MAP and CMAP treatments. There were no significant differences in emergence rate between the SBUs at both rates regardless of P source.

Lag

Seedling emergence was generally two times faster in the clay loam (2.5 - 3 d) than in the sand (4.2 - 6.3 d) (Figure 22). There was little variability in the lags observed for the treatments in the clay loam. However, there was greater variability in the sand, with the shortest lag phase when struvite was narrow-banded (4.2 d) or wide-banded (4.6 d) at the 15 mg P kg^{-1} rate.

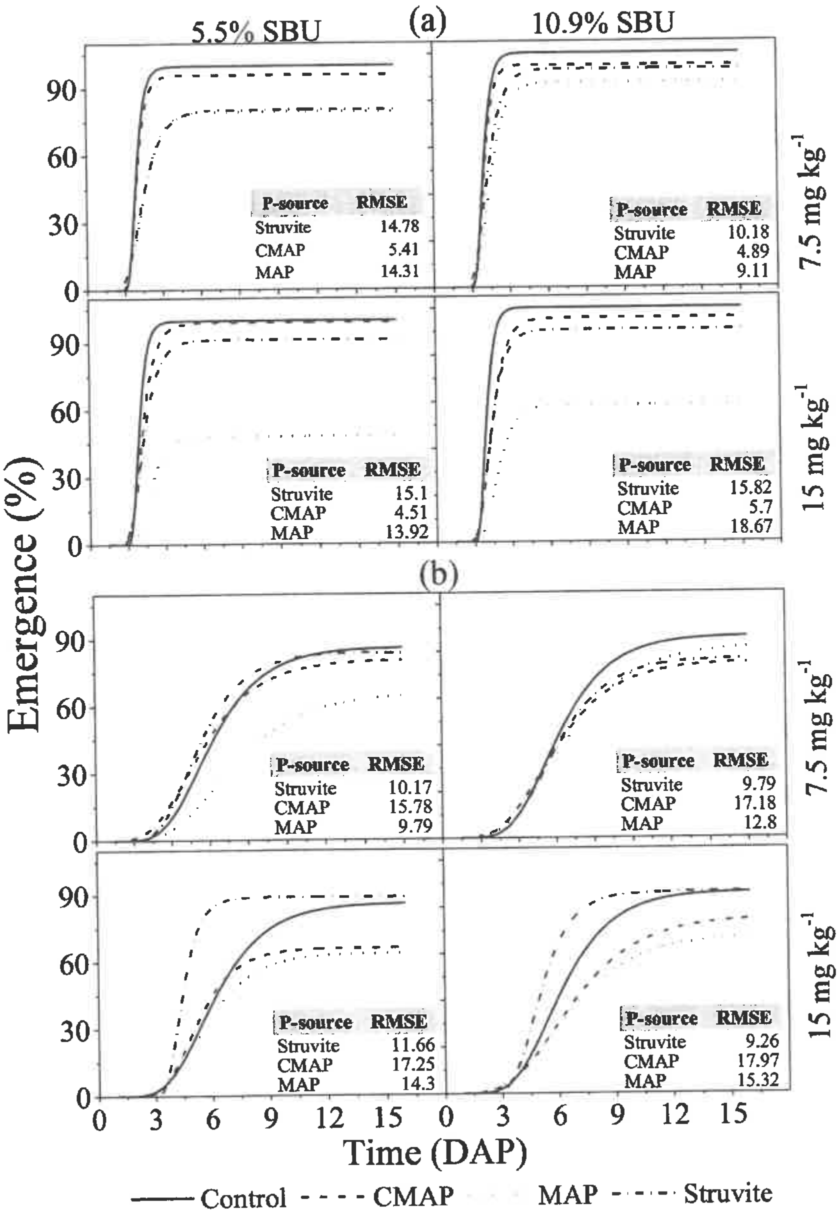

Figure 22. Fitted Gompertz function on canola emergence as affected by P source, rate, SBU, and soil type. The RMSEs for the controls are, 2.56 for the clay loam and 14.71 for the sand.

Discussion

Nonlinear regression analysis using the Gompertz function showed that, on average, seedling emergence in the sand started 2 d later than in the clay loam. This may be due to differences in the texture, aggregation, and OM contents of the soils. These factors led to differences in the container capacity water contents (390 g kg^{-1} for the clay loam vs 260 g kg^{-1} for the sand). Also, the sand and clay loam had bulk densities of 1.3 and 0.9 g cm^{-3}, respectively. The higher bulk density of the sand may have increased its penetration resistance relative to the clay loam, thus leading to reduced seedling emergence. This is consistent with observations by (Nasr and Selles, 1995), who found that bulk density was inversely correlated with emergence speed and total emergence. They argued that the delay in emergence was primarily due to a decrease in the volume of voids at high bulk density, which increased the interfacial stress to the elongating coleoptile. Thus, the lower bulk density, higher water holding capacity, and aggregated structure of the clay loam offered more favorable conditions for seedling development than the sand.

In the clay loam, total seedling emergence decreased by at least 40% relative to the control with application of MAP at 15 mg P kg^{-1}. In contrast, no significant reductions in seedling emergence were observed with struvite and CMAP regardless of rate. The reduction in total emergence at the higher rate of MAP was likely due primarily to the relatively high salt concentrations in the soil solution around MAP granules. Monoammonium phosphate has very high water solubility (~370 g L^{-1}) (Chien et al., 2011) and, when applied in a band, it rapidly increases the osmotic pressure of the soil solution around the fertilizer band (Dubetz et al., 1959). On the other hand, struvite does not rapidly increase soil salt concentrations due to its low solubility (~0.2 g L^{-1} in water) (Bhuiyan et al., 2007), while P release from CMAP is normally slow due to the polymer coating (Shaviv, 2001b). Consequently, MAP has a greater tendency to delay or prevent seed hydration, damage developing embryo cells, and ultimately hinder germination or emergence (Bliss et al., 1986).

Nonlinear regression analysis showed a significant SBU effect of MAP at both rates, CMAP at the 15 mg kg^{-1} rate, and struvite at the 7.5 mg kg^{-1} rate in the clay loam. At the lower SBU, the fertilizer is concentrated in a narrower band, which reduces fertilizer rates that can be safely applied to canola (Thomas, 2003). Nonlinear regression analysis indicated that when fertilizer was applied at the higher (15 mg kg^{-1}) rate and the lower (5.5%) SBU, salt toxicity effects were substantial. Results for the 7.5 mg kg^{-1} rate of struvite are unusual considering the 15 mg kg^{-1} rate for this P-source did not show much toxicity.

In the sand, all MAP treatments, except the wide-banded 7.5 mg P kg^{-1} rate, and the narrow-banded 15 mg P kg^{-1} rate of CMAP significantly lowered final counts relative to the control. However, no significant damage was observed from struvite. Moreover, struvite applied at 15 mg P kg^{-1} significantly improved emergence rate. This may be due to the introduction of some organic matter with the struvite. Organic matter improves the water holding capacity and the aggregation of the soil. On the other hand, relative to other P sources, the damage from MAP in the sand was not as distinct as that in the clay loam. The higher concentration of soluble salts in the clay loam, as well as its higher CEC compared with the sand may have contributed to MAP being more restrictive of seedling emergence in this soil. With high background solute potential, it takes less fertilizer to reach the threshold at which seedlings are damaged (Lindstrom et al., 1976).

The lower final emergence counts for some treatments in the clay loam, which were not accompanied by a corresponding decrease in the emergence rate or an increased delay in emergence, suggest that toxicity effects occurred either at germination or at early seedling development. This is because all seeds that successfully germinated or survived in the earliest seedling development stages seemingly established and emerged at similar rates. The processes leading to emergence, germination and seedling development respond differently to high levels of stress factors such as fertilizer salts (Ashraf and McNeilly, 2004; Bewley, 1997; Huang and Redmann, 1995). Subsurface seedling elongation has relatively higher sensitivity to stress factors than germination (imbibition and radicle emergence) (Lindstrom et al., 1976). Salts affect cell physiological functions more than water uptake, especially under moisture conditions near optimal (Bradford, 1990), such as those in this study. The most critical stage may be early embryonic development, just after completion of germination (Pace and Benincasa, 2010). Therefore, all seedlings surviving this critical phase may have successfully emerged and survived as no seedling injury was observed after emergence for any of the treatments.

Our results are consistent with those from numerous other studies with canola and other crops, which showed toxicity from high rates of MAP (Allred and Ohlrogge, 1964; Nyborg, 1961; Qian and Schoenau, 2010; Qian et al., 2012; Roberts and Harapiak, 1997). In laboratory studies, Qian and Schoenau (2010) found significant canola seedling damage from rates of MAP > 20 kg P_2O_5 ha^{-1} when fertilizer was applied at 15% SBU (3.8 cm spread). The authors reported a > 50% decrease in canola emergence at rates greater than 60 kg P_2O_5 ha^{-1} while no significant damage was observed from CMAP, even at rates greater than 80 kg P_2O_5 ha^{-1}. No previous studies have reported the effects of struvite on canola plant stands.

Conclusions

The study has demonstrated the lower risk associated with seedrow application of slow-release P sources, struvite and CMAP. For the most part, MAP lowered canola emergence more than the SRFs. These results indicate that struvite may be a safe option when canola is grown in P-deficient soils which require the application of large rates of P in the seedrow. This is of particular importance in high P-fixing soils, where PUE is expected to be low, and seedrow application is the best placement method. Supplying adequate P is very important for optimal yield, and having a safer option that can minimize seedling damage, offering the flexibility to apply high rates in contact with the seed, could be worthwhile. These results showed that high rates of MAP could lead to more than 50% reduction in seedling emergence. Reducing seedling damage by using a less toxic P source such as struvite could also help curb losses and costs associated with replanting.

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UNIVERSITY OF MANITOBA

CANOLA COUNCIL OF CANADA
FINAL EXPENDITURES REPORT

FOR THE PERIOD: April 1, 2014 **TO:** June 30, 2014

PROJECT TITLE: Can slow-release monoammonium phosphate and struvite improve phosphorus use efficiency and reduce seedling toxicity in canola? **GRANTEE:** Dr. F. Zvomuya

UNIVERSITY FUND#: 314253-312800-2000 **DATE:** July 18, 2014

PARTICULARS	AMOUNT	TOTAL
1. SALARIES AND BENEFITS:		
Research Associate	$ -	
Support Salaries & Wages	-	
Student Wages	-	
Fellowships Bursaries & Other	3,996.80	
Staff Benefits & Pay Levy	-	3,996.80
2. TRAVEL		497.35
3. PRINTING AND DUPLICATING		-
4. MATERIALS AND SUPPLIES		-
5. TELECOMMUNICATIONS		-
6. OTHER OPERATIONAL EXPENSES		5,560.52
7. EXTERNALLY CONTRACTED SERVICES		-
8. PROFESSIONAL FEES		-
9. CAPITAL ASSET ACQUISITIONS		-
10. REPAIRS AND MAINTENANCE		-
11. LAND & BUILDING ACQUISITIONS AND IMPROVEMENTS		-
12. OVERHEAD		-
		10,054.67

SUMMARY:		
Total Funds Authorized	$ 56,050.00	
Funds Reported Previously	$ 50,445.00	
Current Funds	-	
Total Cumulative Funds		50,445.00
Expenses Reported Previously	$ 45,995.33	
Current Expenses	10,054.67	
Total Cumulative Expenses		56,050.00
Balance at June 30, 2014		$ (5,605.00)

I hereby certify the expenses summarized above were incurred wholly and paid on behalf of the grantee and that vouchers are available for audit.

Maria Tabaquero Date: July 18, 2014

Maria Tabaquero, Research Accountant

I certify that all payments requested are for appropriate purposes and in accordance with the contract.

F. Zvomuya Date: July 18, 2014

Dr. F. Zvomuya, Grantee