Hog-Manure-Recovered Struvite: Effects on Canola and Wheat Biomass Yield and Phosphorus Use Efficiencies

Yeukai Katanda
Dep. of Soil Science
362 Ellis Bldg.
Univ. of Manitoba
Winnipeg, MB, R3T 2N2
Canada

current address:
Environmental and Life Sciences
Trent Univ.
1600 West Bank Drive
Peterborough, ON, K9J 7B8
Canada

Francis Zvomuya*
Don Flaten
Dep. of Soil Science
362 Ellis Bldg
Univ. of Manitoba
Winnipeg, MB, R3T 2N2
Canada

Nazim Cicek
Biosystems Engineering
Univ. of Manitoba
Winnipeg, MB, R3T 2N2
Canada

Core Ideas:
- Struvite recovered from liquid hog manure is a slow-release P source.
- Recovered struvite produced yields that matched or exceeded those from MAP fertilizers.
- Despite its slow-release properties, struvite supplied adequate P to the crops.

Recovery of manure P as magnesium ammonium phosphate hexahydrate (MgNH₄PO₄·6H₂O), commonly known as struvite, can mitigate the risk of P contamination of surface water bodies from hog operations. The slow release of P from struvite may help improve crop P use efficiency. This greenhouse bioassay evaluated the agronomic effectiveness of liquid hog manure recovered struvite. Struvite, monoammonium phosphate (MAP), and polymer-coated MAP (CMAP) were evaluated for canola (Brassica napus L.) grown in rotation with spring wheat (Triticum aestivum L.) in two low soil test P (Olsen P < 6 mg kg⁻¹) soils: a sandy Gleyed Regosol (Typic Haplaquent) and a clay loamy Orthic Black Chernozem (Udic Boroll). The fertilizers were applied either in the seed row or in a sideband at 1.1 and 2.2 g P m⁻² rates. In both soils, struvite produced canola dry matter (DM) yield (DMY, 2.4 g kg⁻¹ soil), P uptake (5.9 mg P kg⁻¹ soil), P recovery efficiency (43%), and agronomic efficiency (0.15 g DM mg⁻¹ P) that were similar to those of MAP and CMAP in the first crop phase. Moreover, at the 2.2 g P m⁻² rate, struvite produced significantly greater canola DMY than MAP in the second crop phase and both MAP and CMAP in the third crop phase. Overall, wheat did not produce significant responses to P fertilization. These results indicate that struvite recovered from liquid hog manure can supply sufficient P to sustain yields and P use efficiency matching or exceeding those for MAP.

Abbreviations: AE, agronomic efficiency; CMAP, polymer-coated monoammonium phosphate; DM, dry matter; DMY, dry matter yield; EC, electrical conductivity; ICP–OES, inductively coupled plasma optical emission spectrometry; MAP, monoammonium phosphate; PPRE, phosphorus recovery efficiency; PU, phosphorus uptake; RO, reverse osmosis; STP, soil test phosphorus.

Intensive hog production in western Canada generates manure at an estimated rate of >16 Tg annually (Hofmann, 2013). Manitoba, which has the third largest hog population (2.8 million as of January 2014) of all Canadian provinces (12.7 million hogs total), accounts for about 20% of Canada’s daily hog manure output (Statistics Canada, 2014a).

Manure from hog operations is typically applied on agricultural land as a source of nutrients for crops. Current regulations in many jurisdictions, including Manitoba, now require that manure be applied based on crop P needs. This is because the N/P ratios of hog manures (2:1–4:1) are typically lower than crop uptake ratios (4:1–7:1) (Nelson and Janke, 2007), with the result that repeated manure applications based on crop N needs can lead to excessive soil test P (STP) levels. Therefore, the amount of hog manure that can be applied on agricultural land without risking noncompliance with the increasingly stringent regulations is limited. Finding suitable land proximal to hog operations can be a daunting task, particularly where soils have received repeated manure applications. This...
would necessitate transfer of manure to and its application on low-P agricultural lands. However, transportation of large volumes of manure across long distances is not economically viable. There is, therefore, a need for alternative manure management options.

A promising alternative is the recovery of P as struvite (magnesium ammonium phosphate hexahydrate $\text{[MgNH}_4\text{PO}_4\text{.6H}_2\text{O]}$) from manure before land application. Pure struvite has an elemental composition of 57 g N, 126 g P, and 99 g Mg kg$^{-1}$. Substantial progress has been made in 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), and swine manure (Jordaan et al., 2010). The higher N/P ratio of manure following the recovery of struvite can be more economically transported for application on distant, low-P soils.

More than 75% of Canadian farmers rely on commercial fertilizers for crop production (Statistics Canada, 2008). Monoammonium phosphate is the most commonly used P fertilizer on the Canadian prairies. In the 2013–2014 season, 2 × 10$^5$ Mg of MAP was shipped to the Canadian market, with 56% of this going to the prairies (Statistics Canada, 2014b). 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 (Elser, 2012).

Struvite has been shown to be an effective P fertilizer for corn ($\text{Zea mays}$ L.; Barak and Stafford, 2006; Gell et al., 2011). When compared with monocalcium phosphate, struvite-fertilized perennial ryegrass ($\text{Lolium perenne}$ L.) produced similar DMY in sandy clay loams with medium to high Olsen P concentrations (Johnston and Richards, 2003). In a greenhouse experiment using Italian ryegrass ($\text{Lolium multiflorum}$ L.) and corn, DMY and P uptake from various urine- and manure-recovered struvites equaled or exceeded those for Cederan phosphate fertilizer (Antonini et al., 2012). Plaza et al. (2007) reported that struvite recovered from an anaerobic digester supernatant was as effective as single superphosphate at increasing DMY and P uptake from various urine- and manure-recovered struvites and superseded MAP (11–52–0 N–P–K). The struvite was analyzed for total P, K, Ca, and Mg in the struvite digests were determined by inductively coupled plasma optical emission spectrometry (ICP–OES) with a PerkinElmer 5400 ICP following digestion with $\text{HNO}_3$–$\text{H}_2\text{O}_2$–$\text{HCl}$ according to a modified USEPA method (USEPA, 1996). Struvite pH was determined in a 1:10 struvite [dry wt./solution] ratio (Mulvaney, 1996). Total P, K, Ca, and Mg in the struvite digests were determined by inductively coupled plasma optical emission spectrometry (ICP–OES) with a PerkinElmer 5400 ICP following digestion with $\text{HNO}_3$–$\text{H}_2\text{O}_2$–$\text{HCl}$ according to a modified USEPA method (USEPA, 1996). Struvite pH was determined in a 1:1 struvite/water suspension. Selected properties of the struvite are summarized in Table 1.

**Soils**

The two soils (0–15-cm layer) used in this bioassay were a dark gray, sandy Gleyed Regosol (Typic Haplaren) from Roseisle (49°33.577′ N, 98°24.824′ W) and a clay loamy Orthic Black Chernozem (Udic Boroll) from Justice (49°58.590′ N, 99°52.908′ W), MB, Canada. Plant-available P in the soils was determined before initial planting and after each harvest using

**Table 1.** Selected chemical properties of struvite recovered from hog manure and commercial fertilizers monoammonium phosphate (MAP) and polymer-coated MAP (CMAP) used in the greenhouse bioassay.

<table>
<thead>
<tr>
<th>Analyte</th>
<th>Struvite</th>
<th>MAP</th>
<th>CMAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total N</td>
<td>57.7</td>
<td>110</td>
<td>100</td>
</tr>
<tr>
<td>$\text{NH}_4$–N</td>
<td>16</td>
<td>110</td>
<td>100</td>
</tr>
<tr>
<td>Total P</td>
<td>100.5</td>
<td>227</td>
<td>223</td>
</tr>
<tr>
<td>K</td>
<td>3.7</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Ca</td>
<td>5</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mg</td>
<td>64</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>pH</td>
<td>5.5</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Moisture, g kg$^{-1}$</td>
<td>400</td>
<td>12</td>
<td>12</td>
</tr>
</tbody>
</table>
the ascorbic acid–molybdate method with a Skalar SAN++ segmented flow analyzer (Skalar Analytical B.V.) following extraction of 5 g of soil with 50 mL of 0.5 mol L$^{-1}$ NaHCO$_3$ at a pH of 8.5 (Olsen et al., 1954). Selected soil properties are presented in Table 2.

**Experimental Setup**

The greenhouse experiment was a randomized complete block design with a factorial plus two controls treatment structure and three replicates. A factorial combination of P source (struvite, MAP, and CMAP), P rate (1.1 and 2.2 g P m$^{-2}$), placement method (seed row and sideband), and soil texture (clay loam and sand) was used. For each soil, a no-P control was included for comparison. Field-moist soil was passed through a 4-mm sieve and thoroughly mixed before weighing (8 kg dry wt.) into 12.5-L square plastic pots with a surface area of 0.055 m$^2$. Bulk densities after fertilizer application, seeding, and packing were approximately 1.3 g cm$^{-3}$ for the sand and 0.9 g cm$^{-3}$ for the clay loam. Before seeding, all pots received 100-mL aliquots of a full-strength nutrient solution from which P was omitted. The composition of the solution was (kg $^{-1}$): 120 mg N as NH$_4$NO$_3$ (corrected for P-source N contribution); 100 mg K as KCl; 20 mg S as (NH$_4$)$_2$SO$_4$; 4 mg Zn as ZnCl$_2$; 2 mg Mn as MnCl$_2$·4H$_2$O; 5 mg Cu as CuSO$_4$·5H$_2$O; 4 mg Fe as Fe(III)-ethylene-diaminetetraacetic acid; 1 mg B as H$_3$BO$_3$; and 0.4 mg Mo as Na$_2$MoO$_4$·2H$_2$O (Zvomuya et al., 2006). Reverse osmosis water was added to bring the soil moisture content to 260 kg g$^{-1}$ in the sand and 390 kg g$^{-1}$ in the clay loam, which correspond to 65 and 61% water-filled pore space, respectively. The pots were weighed and allowed to acclimatize in the greenhouse for 24 h before planting. The weight of each pot was noted and used as the basis for subsequent watering events.

Struvite (57 g N and 101 g P kg$^{-1}$), MAP (110 g N and 227 g P kg$^{-1}$), and CMAP (100 g N and 223 g P kg$^{-1}$) were applied to the potted soils at the rates indicated above. The experimental P rates were determined based on the pot surface area to reflect 17% seedbed utilization (2.5-cm fertilizer band width and 15-cm row spacing). The lower rate (1.1 g P m$^{-2}$) reflects the maximum P rate (12 kg P ha$^{-1}$) currently recommended to minimize canola seedling toxicity when MAP is placed with the seed in the seed row, while the higher rate (2.2 g P m$^{-2}$) reflects the P removal (22 kg P ha$^{-1}$) in the aboveground biomass of a 1600 kg ha$^{-1}$ canola crop (Thomas, 2014). The fertilizers were placed either with the seed (seed-row placement) or 2.5 cm beside and below the seed row (sidebanding) in 2.5-cm-wide bands across the center of each pot. To allow assessment of residual effects, P fertilization was done only in the first crop phase.

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 $\sim$2.5 cm apart and wheat seeds were $\sim$1.2 cm apart, giving target plant densities of 145 m$^{-2}$ for canola and 362 plants m$^{-2}$ for wheat. Canola and wheat were alternately grown in two sequences (one sequence of canola–wheat–canola and the other of wheat–canola–wheat) to facilitate the assessment of residual effects of fertilizer P for three crop phases. The canola–wheat rotation was chosen to reflect common practice on farms in the Canadian prairies. Temperatures in the greenhouse were maintained at 22 ± 3°C under a 16-h photoperiod during the entire study. Throughout the study, the pots were weighed and watered with RO water at least once a week to replenish any moisture lost through evapotranspiration.

Plants were harvested at early flowering (39–43 d after emergence), which corresponded to Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie (BBCH) Stages 50 to 62 for canola (Lancashire et al., 1991) and Zadoks Stages 39 to 57 for wheat (Zadoks et al., 1974). Research has shown that canola seed yield is strongly and positively correlated with DMY (Campbell and Kondra, 1978), and maximum canola biomass accumulation and P uptake rates occur at 21 to 42 d after emergence (Malhi et al., 2007). Plants were harvested by cutting at approximately 2.5 cm above the soil surface using clippers. The harvested aboveground biomass was dried at 60°C for 48 h and weighed for dry mass determination. Dry samples were finely ground (<0.15 mm) before laboratory analysis. Total P in the plant tissue was analyzed by ICP–OES (Thermo iCAP 6300 Radial, Thermo Electron Corporation) following digestion of 0.5 g of ground plant tissue with 10 mL of concentrated HNO$_3$ at 175°C for 15 min using a MARS 5 microwave system (CEM Corporation).

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

<table>
<thead>
<tr>
<th>Property†</th>
<th>Sand</th>
<th>Clay loam</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO$_3$–N, mg kg$^{-1}$</td>
<td>11</td>
<td>53</td>
</tr>
<tr>
<td>Olsen P, mg kg$^{-1}$</td>
<td>3.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Mg, mg kg$^{-1}$</td>
<td>192</td>
<td>907</td>
</tr>
<tr>
<td>Ca, mg kg$^{-1}$</td>
<td>2348</td>
<td>3823</td>
</tr>
<tr>
<td>K, mg kg$^{-1}$</td>
<td>49</td>
<td>203</td>
</tr>
<tr>
<td>Cl, mg kg$^{-1}$</td>
<td>98</td>
<td>11</td>
</tr>
<tr>
<td>S, mg kg$^{-1}$</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>B, mg kg$^{-1}$</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Zn, mg kg$^{-1}$</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Fe, mg kg$^{-1}$</td>
<td>15</td>
<td>19</td>
</tr>
<tr>
<td>Mn, mg kg$^{-1}$</td>
<td>2.1</td>
<td>5.3</td>
</tr>
<tr>
<td>Cu, mg kg$^{-1}$</td>
<td>0.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Na, mg kg$^{-1}$</td>
<td>24</td>
<td>17</td>
</tr>
<tr>
<td>Organic C, g kg$^{-1}$</td>
<td>9.3</td>
<td>34</td>
</tr>
<tr>
<td>CEC, cmolc kg$^{-1}$</td>
<td>14</td>
<td>27</td>
</tr>
<tr>
<td>CCE, g kg$^{-1}$</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>EC, dS m$^{-1}$</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>pH</td>
<td>8.0</td>
<td>7.6</td>
</tr>
<tr>
<td>Field capacity, kg kg$^{-1}$</td>
<td>0.1</td>
<td>0.3</td>
</tr>
</tbody>
</table>

† NO$_3$–N, Cd reduction (Mulvaney, 1996b); Ca, Mg, K, and Na, atomic absorption spectroscopy (Thermo Scientific iCE 3300 AAS) following extraction of 5 g of soil with 33 mL of NH$_4$OAc at pH 7; CEC (cation exchange capacity), summation of basic cations; CCE, CaCO$_3$ equivalence; EC (electrical conductivity) and pH, 1:1 (w/w) soil/water suspension using Accumet AB and Accumet AB30 meters, respectively (Fisher Scientific); soil organic C concentration, loss on ignition (Nelson and Sommers, 1996).
After each harvest, the soil in each pot was thoroughly mixed and a sample (~20-g dry wt.) was taken, air dried, and passed through a 2-mm sieve before determination of the residual Olsen P concentration. Roots were chopped and mixed back into the remaining soil. After repotting the soil, 50 mL of a 0.6 mol L⁻¹ CuSO₄·5H₂O solution was added to each pot and thoroughly mixed with the soil, giving a rate of 5 mg Cu kg⁻¹. This was necessary to prevent Cu deficiency symptoms observed in the first wheat crop. The pots were then left fallow for 14 d before reseeding with the second or third alternate crop in the rotation. A no-P nutrient solution containing half the nutrients added in the first phase was added, along with RO water, to bring the moisture content to the same level as in the first crop phase.

### Calculations

Phosphorus uptake (PU, mg P kg⁻¹ soil) by plant shoots (aboveground biomass) in each pot was calculated as

\[ \text{PU} = \text{DMY} \times P_{\text{conc}} \]  

where \( \text{DMY} \) is the shoot dry matter yield (g kg⁻¹ soil) and \( P_{\text{conc}} \) is the corresponding shoot P concentration (mg g⁻¹).

Fertilizer P recovery efficiency (PRE, %) was calculated as the difference in P uptake between fertilized (PUₐₜ, g P kg⁻¹) and unfertilized (PU₀, g P kg⁻¹) plants, expressed as a percentage of the fertilizer P applied (\( P_{\text{app}} \), g kg⁻¹):  

\[ \text{PRE} = \left( \frac{\text{PU}_{\text{fert}} - \text{PU}_0}{P_{\text{app}}} \right) \times 100 \]  

Agronomic efficiency (AE, g DM g⁻¹ P), which is the amount of DM produced per unit P applied, over and above the biomass yield from the no-P control, was calculated as

\[ \text{AE} = \left( \frac{\text{DM}_{fert} - \text{DM}_0}{P_{\text{app}}} \right) \]  

where \( \text{DM}_{fert} \) is the DMY from the fertilized pots and \( \text{DM}_0 \) is the DMY from the no-P control. The assumptions when using the difference method are that P uptake and yield in the fertilized soil is solely dependent on the applied P and not on increased uptake from the soil P reserves due to enhanced plant vigor from the added P fertilizer (Syers et al., 2008).

Cumulative PU was the total P uptake summed across all three crops in each of the two crop sequences, canola–wheat–canola and wheat–canola–wheat:

\[ \text{Cumulative PU} = \text{PU}_1 + \text{PU}_2 + \text{PU}_3 \]  

where \( \text{PU}_1 \), \( \text{PU}_2 \), and \( \text{PU}_3 \) are the PU values for the first, second, and third crop phases, respectively. A similar calculation was done for cumulative PRE.

### Statistical Analysis

A repeated measures analysis of variance (ANOVA) was performed using the GLIMMIX procedure of SAS Version 9.4 (SAS Institute, 2014). Treatment effects were considered significant at \( P < 0.05 \). The Tukey–Kramer multiple comparison procedure was used to compare treatment means. Consistent with the factorial plus control design, the ANOVA was performed in two steps: (i) comparison of fertilized treatments with the unfertilized controls and (ii) comparison of fertilized treatments excluding the controls (full 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. Based on the Akaike information criterion, the following covariance structures were used: (i) compound symmetry for canola DMY, PU, PRE, and wheat PRE; (ii) unstructured for wheat DMY; heterogeneous autoregressive for canola AE and wheat PU; and heterogeneous compound symmetry for wheat AE. Cumulative PU and PRE data were also analyzed using the GLIMMIX procedure, with crop sequence, soil, P source, P rate, and placement method as fixed effects and block as a random effect.

### RESULTS

#### Dry Matter Yield

**Canola**

When canola DMY data were analyzed with the unfertilized controls included, there were significant \( P < 0.001 \) canola DMY responses to P fertilization in both soils for the first crop after P application (that is, the first crop phase in the canola–wheat–canola sequence). In the second crop phase, all struvite treatments, seed-placed MAP, and CMAP at 2.2 g P m⁻², MAP sidebanded at 2.2 g P m⁻², and CMAP sidebanded at 1.1 g P m⁻² produced significant responses in the clay loam. In the third crop phase, significant responses to seed-row-placed and sidebanded struvite and seed-row-placed MAP and CMAP were observed in the clay loam at the 2.2 g P m⁻² rate. In contrast, there were no significant canola DMY responses to P application in the sand in Crop Phases 2 and 3 (Supplemental Table S1).

Analysis of variance of DMY data from a factorial combination of treatments (excluding the controls) showed a significant P source × crop phase interaction (Table 3). While canola DMY did not differ significantly among P sources in the first crop phase, struvite produced significantly greater DMY than MAP in the second crop phase and both MAP and CMAP in the third crop phase (Fig. 1a). Overall, DMY significantly declined with each subsequent crop phase for all P sources.

There was also a significant P source × P rate interaction for canola DMY averaged across all crop 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 1.1 g P m⁻² rate (Fig. 1b). There were significant increases in canola DMY when struvite and MAP were applied at the 2.2 g P m⁻² rate compared with the 1.1 g P m⁻² rate, but the P rate effect was not significant for CMAP.

Phosphorus placement method effects varied significantly with crop phase. In the first crop phase, seed-row placement
produced significantly greater DMY than sidebanding, but no significant differences were observed in the second and third crop phases (Fig. 2a).

Table 3. Canola and wheat dry matter yield (DMY), P uptake, P recovery efficiency (PRE), agronomic P efficiency (AE), and residual Olsen P as affected by struvite, monoammonium phosphate (MAP), and polymer-coated MAP (CMAP) application.

<table>
<thead>
<tr>
<th>Effect</th>
<th>DMY</th>
<th>P uptake</th>
<th>PRE</th>
<th>AE</th>
<th>Residual Olsen P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Canola</td>
<td>Wheat</td>
<td>Canola</td>
<td>Wheat</td>
<td>Canola</td>
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<tr>
<td>Crop phase (C)</td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>1</td>
<td>2.4</td>
<td>1.9</td>
<td>5.9</td>
<td>4.7</td>
<td>42.8</td>
</tr>
<tr>
<td>2</td>
<td>1.8</td>
<td>1.5</td>
<td>3.6</td>
<td>3.0</td>
<td>13.4</td>
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<td>3</td>
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<td>1.4</td>
<td>1.9</td>
<td>2.7</td>
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<td>P source (P)</td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td>CMAP</td>
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<td>1.6</td>
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<td>19.7</td>
</tr>
<tr>
<td>MAP</td>
<td>1.8</td>
<td>1.6</td>
<td>3.8</td>
<td>3.6</td>
<td>20.0</td>
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<tr>
<td>Struvite</td>
<td>1.9</td>
<td>1.6</td>
<td>4.0</td>
<td>3.3</td>
<td>20.8</td>
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<tr>
<td>P rate (R, g P m⁻²)</td>
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<td>Placement (Ap)</td>
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<td>Seed row</td>
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<td>3.5</td>
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<td>Sideband</td>
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<td>1.6</td>
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<td>Soil (S)</td>
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<tr>
<td>Clay loam</td>
<td>1.8</td>
<td>1.8</td>
<td>3.6</td>
<td>4.1</td>
<td>23.3</td>
</tr>
<tr>
<td>Sand</td>
<td>1.8</td>
<td>1.3</td>
<td>4.0</td>
<td>2.8</td>
<td>17.0</td>
</tr>
</tbody>
</table>

P value

- C <0.001 <0.001 <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 <0.001 0.004
- R <0.001 <0.001 <0.001 <0.001 0.002 0.33 <0.001 0.62 <0.001 <0.001
- S 0.12 <0.001 0.01 <0.001 <0.001 0.66 <0.001 0.29 <0.001 <0.001
- Ap 0.01 0.15 0.87 0.74 0.72 0.40 0.19 0.61 0.54 0.86
- P × C 0.004 0.61 0.38 0.01 0.25 0.17 0.003 0.96 0.04 0.02
- P × R 0.04 0.70 0.52 0.84 1.00 0.61 0.48 0.47 0.001 0.43
- P × S 0.07 0.50 0.14 0.58 0.01 0.56 0.53 0.92 0.003 0.0003
- P × Ap 0.63 0.15 0.81 0.68 0.87 0.81 0.68 0.18 0.13 0.86
- R × C 0.03 0.86 <0.001 0.02 0.001 0.54 <0.001 0.049 <0.001 <0.001
- R × S 0.01 1.00 0.37 0.06 0.52 0.10 0.55 1.00 0.06 0.15
- R × Ap 0.18 0.36 0.94 0.21 0.79 0.26 0.77 0.84 0.73 0.31
- S × C <0.001 <0.001 <0.001 <0.001 <0.001 <0.001 <0.001 <0.001 <0.001 <0.001
- Ap × C 0.001 0.13 0.81 0.73 0.65 0.46 0.001 0.22 0.87 0.51
- Ap × S 0.41 0.54 0.85 0.29 0.97 0.78 0.80 0.32 0.73 0.31
- R × S × C 0.001 0.61 0.01 0.67 0.67 0.01 0.03 0.39 0.57 0.92
- P × S × C 0.24 0.01 0.69 0.45 0.42 0.73 0.69 0.29 0.09 0.22
- P × R × C 0.75 0.69 0.79 0.60 0.40 0.81 0.24 0.94 0.06 0.22
- P × Ap × C 0.73 0.88 0.91 0.96 0.86 0.96 0.66 0.94 0.94 0.049
- R × Ap × C 0.61 0.70 0.82 0.80 0.82 0.74 0.82 0.27 0.96 0.62
- Ap × S × C 0.63 0.15 0.72 0.35 0.85 0.41 0.52 0.49 0.36 0.73
- P × R × S 0.25 0.73 0.90 0.93 0.17 0.88 0.30 0.66 0.08 0.30
- P × Ap × S 0.97 0.63 0.98 0.37 0.88 0.30 0.56 0.70 0.03 0.04
- R × Ap × S 0.15 0.33 0.66 0.69 0.35 0.94 0.61 0.84 0.17 0.92
- P × R × Ap 0.22 0.69 0.69 0.50 0.62 0.39 0.56 0.97 0.53 0.86
- P × R × Ap × C 0.91 0.74 0.93 0.64 0.70 0.95 0.97 0.99 0.75 0.60
- P × R × S × C 0.40 0.87 0.87 0.41 0.53 0.85 0.88 0.92 0.40 0.59
- P × Ap × S × C 0.41 0.62 0.36 0.93 0.75 1.00 0.65 0.93 0.33 0.20
- R × Ap × S × C 0.64 0.83 0.78 0.63 0.92 0.97 0.35 0.97 0.34 0.76
- P × R × Ap × S 0.86 0.83 0.89 0.86 0.99 0.95 0.64 0.83 0.57 0.04
- P × R × Ap × S × C 0.88 0.83 0.93 0.94 0.99 0.99 0.78 0.91 0.37 0.44

The effect of the P rate on canola DMY varied with soil and crop phase, as indicated by the significant P rate × soil × crop phase effect (Table 3). Averaged across P sources, canola DMY in the third
crop phase was significantly greater for the 2.2 g P m\(^{-2}\) rate than for the 1.1 g P m\(^{-2}\) rate in the clay loam (Fig. 2b). By comparison, there were no significant differences between P rates in the first and second crop phases in the clay loam or in any crop phase in the sand.

**Wheat**

When all treatments, including the control, were considered, the only significant wheat DMY response to P application in the first crop phase was in the sand, when MAP was applied in the seed row at the 1.1 g P m\(^{-2}\) rate (2.3 vs. 1.2 g kg\(^{-1}\) for the control). In the second and third crop phases, there was no significant DMY response to any treatment in either soil (Supplemental Table S1).

For the fertilized treatments (i.e., the factorial component), wheat DMY significantly varied with P rate (Table 3). The 2.2 g P m\(^{-2}\) rate produced significantly greater wheat DMY (1.7 g kg\(^{-1}\)) than the 1.1 g P m\(^{-2}\) 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 \(\times\) P source \(\times\) crop phase interaction. In the sand, wheat DMY averaged across all P sources significantly decreased from the first crop phase (2.0 g kg\(^{-1}\)) to the second (1.0 g kg\(^{-1}\)), with no further significant decrease in the third (1.0 g kg\(^{-1}\)) (Supplemental Fig. S1). 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 any crop phase.

**Phosphorus Uptake**

**Canola**

In the first crop phase, PU (averaged across soils, placement methods, and P rates) was significantly greater in P-fertilized soils than in the controls, but there were no further responses in PU to P application in the second and third crop phases (Supplemental Table S2).

Analysis of variance of data excluding the controls showed a significant P rate \(\times\) soil \(\times\) crop phase interaction on PU by canola (Table 3). Phosphorus uptake was greater at the 2.2 g P m\(^{-2}\) rate than at the 1.1 g P m\(^{-2}\) rate in the first crop phase in both soils. However, no significant differences were observed in subsequent crop phases (Fig. 3). Also, no significant differences were observed among the P sources or between placement methods in either soil, regardless of crop phase. Phosphorus uptake, averaged across P sources and placement methods, generally declined with subsequent canola phases at both P rates, except for the 2.2 g P m\(^{-2}\) rate in the sand, which showed no decrease after the second crop phase.

**Wheat**

Relative to the control, there was a significant increase in PU by wheat when
MAP was applied at 2.2 g P m⁻² (1.8 vs. 5.9 g mg⁻¹, respectively) in the first crop after P application but only for the sand. No significant responses were observed for CMAP or struvite in this soil or from any treatment in the clay loam in this crop phase. Also, none of the treatments significantly increased wheat PU relative to the control in either soil in the second and third crop phases (Supplemental Table S2).

For the factorial component, P source effects on wheat PU were significant but varied with crop phase, as indicated by the significant P source × crop phase interaction (Table 3). In the first crop phase, PU by wheat was significantly lower with the application of struvite (4.1 g mg⁻¹) than with MAP (5.1 g mg⁻¹) or CMAP (4.9 g mg⁻¹) (Supplemental Fig. S2a). By comparison, P source differences were not significant in the second and third crop phases.

There was a significant P rate × crop phase interaction for PU (Table 3). In the first crop phase, PU from all P sources was significantly greater at the 2.2 g P m⁻² rate (5.2 g mg⁻¹) than at the 1.1 g P m⁻² rate (4.2 g mg⁻¹) (Supplemental Fig. S2b). However, the P rate effects were not significantly different in the second and third crop phases.

There was also a significant soil × crop phase interaction on wheat PU (Table 3). Phosphorus uptake was significantly greater in the clay loam (3.6 g mg⁻¹) than in the sand (2.3 g mg⁻¹) in the second and third crop phases (3.7 g mg⁻¹ for the clay loam vs. 1.7 g mg⁻¹ for the sand), but there was no significant difference between the soils in the first crop phase (5.0 vs. 4.4 g mg⁻¹) (Supplemental Fig. S2c). Overall, wheat PU significantly declined in the second crop phase (3.0 g mg⁻¹) relative to the first crop phase (4.7 g mg⁻¹), but there was no significant decline in the third crop phase (2.7 g mg⁻¹).

**Phosphorus Recovery Efficiency**

**Canola**

There was a significant P source × soil interaction for PRE of canola averaged across crop phases. Struvite and CMAP produced significantly greater PRE in the clay loam than in the sand (Fig. 4a). However, within each soil, the PRE was not significantly different among the P sources and ranged between 21 and 26% in the clay loam and between 16 and 19% in the sand.

There was also a significant P rate × crop phase interaction for PRE (Table 3). In the first crop phase, PRE, averaged across P sources, soils, and placement methods, was significantly greater at the 1.1 g P m⁻² rate (47%) than at the 2.2 g P m⁻² rate (39%) (Fig. 4b). By comparison, no significant differences were detected between the P rates in the second (mean PRE = 14%) and third (4%) crop phases.

Phosphorus recovery efficiency differed significantly with soil, but the soil effect varied with the crop phase (Table 3). Canola PRE was significantly greater in the sand (46%) than in the clay loam (40%) in the first crop phase (Fig. 4c). The oppo-
site was observed in subsequent crop phases, with significantly greater PRE in the clay loam than in the sand (19% for the clay loam vs. 8% for the sand in the second crop phase and 12 vs. −3% for the third crop phase).

**Wheat**

There was a significant P rate × soil × crop phase interaction for the PRE of wheat (Table 3). In the first crop phase, PRE at the 1.1 g m⁻² rate was significantly greater in the sand (27%) than in the clay loam (9%) (Supplemental Fig. S3). By comparison, in the third crop phase, the PRE at the 1.1 g P m⁻² rate was significantly lower in the sand (−6%) than in the clay loam (20%). However, PRE at the 2.2 g P m⁻² rate did not differ significantly between the two soils in any crop phase. Phosphorus recovery efficiency at both P rates significantly declined from the first (24%) to the second crop phase (8%) in the sand, with no significant changes thereafter (−1%). However, at both P rates, PRE in the clay loam did not vary significantly among crop phases. In both soils and all crop phases, PRE did not differ significantly among the P sources.

**Agronomic Phosphorus Use Efficiency**

**Canola**

Phosphorus source effects on the AE of canola were significant but varied with crop phase, as indicated by the significant P source × crop phase interaction (Table 3). For all P sources, AE significantly decreased from the first to the second crop phase (Fig. 5a). However, only struvite and CMAP produced subsequently lower AE in the third crop phase, with no significant change in AE for MAP. No significant differences were detected between struvite and MAP or CMAP in any of the crop phases.

There was a significant placement × crop phase interaction for AE (Table 3). Seed-row placement produced significantly greater AE than sidebanding in the first crop phase (Fig. 5b). However, there were no significant differences between the placement methods in the second and third crop phases. For both placement methods, AE decreased significantly with subsequent crop phases.

There was also a significant P rate × soil × crop phase interaction for canola AE (Table 3). In the clay loam, AE was significantly greater at the 1.1 than at the 2.2 g P m⁻² rate in the first and second crop phases. In contrast, the 2.2 g P m⁻² rate produced significantly greater AE than the 1.1 g P m⁻² rate in the third crop phase. For the sand, the 1.1 g P m⁻² rate produced significantly greater AE than the 2.2 g P m⁻² rate in the first crop phase, with no significant differences between the P rates in subsequent crop phases (Fig. 5c).

**Wheat**

There was a significant P rate × crop phase effect on the AE of wheat (Table 3). For both P rates, AE was significantly greater in the first crop phase (0.06 g DM mg⁻¹ P) than in the second (0.01 g DM mg⁻¹ P), with no significant change in the third crop phase (0.03 g DM mg⁻¹ P) (Supplemental Fig. S4a).
The AE was significantly greater in the first crop phase (0.07 g DM mg⁻¹ P) than in the third crop phase (0.02 g DM mg⁻¹ P) for the 1.1 g P m⁻² rate. However, for the 2.2 g P m⁻² rate, the numerical increase in AE from the second (0.02 g DM mg⁻¹ P) to the third crop phase (0.03 g DM mg⁻¹ P) resulted in no significant difference between AE values in the first (0.05 g DM mg⁻¹ P) and third (0.031 g DM mg⁻¹ P) crop phases.

There was also a significant soil × crop phase interaction for AE (Table 3; Supplemental Fig. S4b). In both soils, AE was significantly less in the second than in the first crop phase. However, AE in the clay loam was significantly greater in the third than in the second crop phase, while no significant difference between the two crop phases was observed in the sand.

**Crop Sequence Effects on Cumulative Phosphorus Uptake and Recovery Efficiency**

There was a significant P rate effect on cumulative PU and PRE averaged across crop sequences (Table 4). Cumulative PU was greater at the 2.2 than the 1.1 g P m⁻² rate. The trend for PRE was opposite, with slightly less PRE for the 2.2 than the 1.1 g P m⁻² rate.

Phosphorus uptake was significantly affected by the starting crop in the sequence, but the differences varied with soil (Table 4). 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 (Fig. 6a).

Overall, PRE was significantly greater for the canola–wheat–canola crop sequence (overall PRE = 55%) than for the wheat–canola–wheat sequence (overall PRE = 38%) (Table 4). Also, struvite produced greater PRE in the clay loam (54%) than in the sand (35%), but there were no significant soil effects for MAP or CMAP (Fig. 6b).

**DISCUSSION**

Struvite showed relatively strong performance for both canola and wheat, producing DMY, PRE, and AE values similar to the commercial P sources in the first crop phase after P application. These results corroborate findings from numerous other studies that demonstrated various recovered struvite products to be of similar effectiveness to commercial P fertilizers for yields of spring wheat (Massey et al., 2009), corn (Barak and Stafford, 2006; Gell et al., 2011), and ryegrass (Antonini et al., 2012; Johnston and Richards, 2003; Plaza et al., 2007). In contrast, Ackerman et al. (2013) reported lower canola DMY and P

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**Table 4. Cumulative P uptake (PU) and P recovery efficiency (PRE) as affected by crop sequence, P source (struvite, monoammonium phosphate [MAP], or polymer-coated MAP [CMAP]), P rate, application method, and soil.**

<table>
<thead>
<tr>
<th>Effect</th>
<th>Cumulative PU</th>
<th>Cumulative PRE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg P kg⁻¹</td>
<td>%</td>
</tr>
<tr>
<td>Crop sequence (Cs)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canola–wheat–canola</td>
<td>10.7</td>
<td>54.5</td>
</tr>
<tr>
<td>Wheat–canola–wheat</td>
<td>11.0</td>
<td>37.9</td>
</tr>
<tr>
<td>P source (P)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMAP</td>
<td>10.9</td>
<td>46.9</td>
</tr>
<tr>
<td>MAP</td>
<td>10.9</td>
<td>47.1</td>
</tr>
<tr>
<td>Struvite</td>
<td>10.8</td>
<td>44.6</td>
</tr>
<tr>
<td>Rate (R, g P m⁻²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>9.6</td>
<td>49.8</td>
</tr>
<tr>
<td>2.2</td>
<td>12.1</td>
<td>42.6</td>
</tr>
<tr>
<td>Application method (Ap)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seed row</td>
<td>10.9</td>
<td>45.9</td>
</tr>
<tr>
<td>Sideband</td>
<td>10.8</td>
<td>46.5</td>
</tr>
<tr>
<td>Soil (S)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay loam</td>
<td>11.5</td>
<td>51.1</td>
</tr>
<tr>
<td>Sand</td>
<td>10.2</td>
<td>41.3</td>
</tr>
</tbody>
</table>

P value†

| P   | 0.92 | 0.58  |
| Ap  | 0.31 | 0.78  |
| Cs  | 0.19 | <0.001|
| R   | <0.001| 0.002 |
| S   | <0.001| <0.001|
| P × S| 0.06 | 0.02  |
| Cs × S| <0.001 | 0.22 |

† Two-, three-, four-, and five-way interactions with P > 0.1 for both parameters are not presented.

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Fig. 6. Effects of (a) soil texture and crop sequence on cumulative P uptake and (b) P source (struvite, monoammonium phosphate [MAP], or polymer-coated MAP [CMAP]) and soil texture on cumulative P recovery efficiency (PRE) of three crop phases of canola–wheat crop sequences. 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.
uptake for hog-manure-recovered struvite compared with MAP and CMAP. This may be explained by the differences between the P-deficient soils (<6 mg Olsen P kg\(^{-1}\)) used in the present study and the sandy loam of medium STP concentration (12 mg Olsen P kg\(^{-1}\)) used by Ackerman et al. (2013). It is likely that P release from recovered struvite was more rapid in our P-deficient soils due to the lower concentration of PO\(_4^{3-}\) in the soil solution (Bhuiyan et al., 2007).

In the clay loam, struvite produced greater canola DMY than MAP in the second crop phase and greater DMY than either MAP or CMAP in the third crop phase. This suggests that struvite can effectively supply P to canola for longer durations than MAP or CMAP. Overall, the PRE of the preceding wheat crops was <10% for all P sources; thus, >90% of the fertilizer P remained potentially available for subsequent crops. Nevertheless, more of the struvite P remained available for longer than the P from the commercial sources in this soil. The long-term (that is, beyond the first 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 from struvite. 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 clay loam used in this study, where rapidly released P is quickly precipitated into forms that are not readily available (Ige et al., 2005).

Unlike canola, wheat showed no significant DMY and PU responses to P application in all crop phases. Research has shown that not all wheat cultivars respond to P application in most soils, regardless of STP level (Korkmaz et al., 2009; Yaseen and Malhi, 2009). Although we did not measure arbuscular mycorrhizal fungal infection in this study, arbuscular mycorrhizal symbiosis between wheat and soil fungi may explain the poor response of the wheat to P application (Shukla et al., 2012). Overall, wheat PRE from all sources was similar and very low (<30%) in the first crop phase. Thus, although wheat P uptake from struvite was significantly lower than that from MAP and CMAP in the first phase, this did not translate into significantly lower wheat DMY or AE for struvite.

Increasing the P application rate from 1.1 to 2.2 g P m\(^{-2}\) significantly increased the mean wheat DMY for all three crop phases. For canola, only struvite and MAP P rate increases led to corresponding increases in DMY. These results indicate that although the dissolution rate and mechanism of P release from struvite in soils has not yet been studied, P availability from struvite may increase with increasing P rate, similar to soluble fertilizers such as MAP. On the other hand, the rate of P release from CMAP is controlled by mass flow and diffusion (Shaviv, 2001), and an increase in the fertilizer rate may not significantly improve the P supply rate if the threshold for P release has been exceeded unless the polymer coating has ruptured and P release is no longer slow or controlled.

Averaged across all P sources, increasing the P application rate increased P uptake by both crops but did not significantly increase DMY and residual STP levels in the first crop phase (Fig. 2b and 3). An increase in canola P uptake with increasing P rates without corresponding increases in canola shoot biomass has also been reported in field studies (Bélanger et al., 2015). 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 (Bélanger et al., 2015; Grant and Bailey, 1993). The suboptimal P levels in the canola tissue observed at the lower rate indicate that the 1.1 g P m\(^{-2}\) rate may not supply sufficient P throughout canola growth in P-deficient soils, although the observed early flowering biomass was similar to that for the 2.2 g P m\(^{-2}\) rate.

For all P sources, seed-row placement was more efficient for canola DMY and AE than sidebanding in the first crop phase. Despite the observed reduction in canola seedling counts in the first crop phase in the sand (data not shown) with seed-row placement (82%) relative to sidebanding (97%), overall, the canola DMY in this study did not appear to have been adversely affected by toxicity due to seed-row placement (Fig. 2). This is because seed-row placement improves the accessibility of P during early seedling development (Grant and Bailey, 1993), and the canola biomass can compensate for low plant stands (Hocking et al., 2003). A reduction in the early-season DMY of >30% is required to significantly reduce the canola seed yield (Bélanger et al., 2015). This placement effect was not observed in the second and third crop phases, mainly due to the mixing of the soil before planting and also because no more P fertilizers were applied at the start of these crop phases.

Averaged across all P sources and rates, the PRE values of both canola and spring wheat in the first crop phase were significantly greater in the sand than in the clay loam. Based on baseline soil properties (Table 2), there may have been greater short-term availability of P in the sand due to the relatively lower P retention capacity compared with the clay loam (Ige et al., 2005). For struvite and CMAP, the overall canola PRE for all three phases was significantly greater in the clay loam than the sand. The P supply from these slow-release P sources is determined by soil moisture conditions, and the higher water holding capacity of the clay loam may have led to faster P release than in the sand.

Phosphorus uptake from the canola–wheat–canola crop sequence was nearly 20% greater than that from the wheat–canola–wheat sequence. Our results also show that the PRE 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 than wheat, as shown in this study (Table 3) and in others (Bolland, 1997; Brennan and Bolland, 2001, 2009; Föhse et al., 1991). Canola 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. In addition, the increases in phosphatase activity and the abundance and diversity of P-solubilizing soil microbes in the rhizosphere of the preceding canola crop may have improved the P supply for the successive wheat crop, leading to consistently high wheat yields.
in the second and third crop phases in the clay loam (Solaíman et al., 2007).

The strong overall performance of struvite occurred despite its slow-release properties, which are attributed to P forms of low solubility. Phosphorus availability from the recovered struvite was largely controlled by MgNH₄PO₄·6H₂O, which accounted for > 80% of the P in the product (Jordaan et al., 2010). In pure water, the solubility of MgNH₄PO₄·6H₂O at 25°C is in the range of 160 to 200 mg L⁻¹ (Barak and Stafford, 2006; Bhuiyan et al., 2007). Given the alkaline pH of the clay loam (pH 7.6) and the sand (pH 8.0) and the moderate temperatures (19–26°C) of the present study, P release from the struvite into the soil solution was generally expected to be slow (Barak and Stafford, 2006). Also, the P in Ca phosphates and organic P forms of the struvite product was potentially slowly available due to low solubility and a high dependence on mineralization rates, respectively (Sharpley et al., 2003). The results of this study suggest that although struvite P might be slowly released, the P release rate may be able to match the canola P uptake rate and hence lead to an adequate P supply matching that of conventional MAP.

CONCLUSIONS

Overall, the hog-manure-recovered struvite product used in this study showed potential to supply P and support canola and spring wheat DMY as effectively as MAP and CMAP. Also, when struvite is used in canola–wheat rotations, there is a potential for greater residual P availability for subsequent canola crops than with MAP or CMAP. In this greenhouse bioassay, the soil was left to rest for only 14 d, was not subjected to freeze–thaw or wet–dry cycles, and the crops were not grown to maturity. Therefore, there is a need for field-scale studies to validate the promising findings from this greenhouse bioassay under more variable conditions. In addition, the P-release rate from struvite in different soils needs to be evaluated to provide a better understanding of the mechanisms of P transfer from this P source.

If hog-manure-recovered struvite is as effective as suggested by the findings of this bioassay, it may be a viable alternative to the widely used MAP in canola–wheat rotations and to high-technology controlled-release fertilizers such as CMAP. Its adoption within agricultural systems would be a good incentive for more intensive recycling of P from livestock operations. The environmental and manure management benefits of struvite recovery and use have the potential to offset the additional production costs.

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REFERENCES
