HOG MANURE–RECOVERED STRUVITE AS A PHOSPHORUS SOURCE FOR ENHANCED PHOSPHORUS USE EFFICIENCY AND REDUCED SEEDLING TOXICITY IN CANOLA

by

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ABSTRACT

Hog manure phosphorus (P) can be recovered as struvite or magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4 \cdot 6H_2O$). The recovered struvite has slow-release properties and may be used as a P-source for crops. Two pot experiments were conducted to evaluate the agronomic effectiveness and seedling toxicity of liquid hog manure-recovered struvite for canola *(Brassica spp.)* and wheat (*Triticum aestivum*). While wheat was non-responsive to P application, canola dry matter yield (DMY) from struvite (1.9 g kg^{-1}) was similar to that from monoammonium phosphate (MAP) (1.8 g kg^{-1}) and coated-monoammonium phosphate (CMAP) (1.7 g kg^{-1}). Importantly, when P was seed-placed at the higher rate (15 mg kg^{-1}), canola seedling emergence was significantly greater with struvite (90%) and CMAP (85%) than with MAP (60%). The results demonstrate the potential of struvite as an effective P-source for canola in P-deficient soils, which can be safely applied at higher rates than those currently recommended for seed-placed MAP.

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DEDICATION

With all my love to my son Tafara, whose love, patience, and understanding during my absence were not in vain.

FOREWORD

The guidelines for thesis preparation set by the Department of Soil Science of the University of Manitoba (http://umanitoba.ca/faculties/afs/dept/soil_science/) were followed in the preparation of this thesis. The thesis is comprised of 4 chapters: a general introduction, 2 research chapters prepared and formatted for submission to the Journal of Environmental Quality (Chapter 2) and the Soil Science Society of America Journal (Chapter 3), and an overall synthesis. I am the principal author of the draft manuscripts from this thesis work, with Drs. Zvomuya, Flaten and Cicek as co-authors. The research chapters are based on greenhouse and growth room experiments conducted at the Fort Garry Campus of the University of Manitoba. The struvite product used was obtained from Dr. Cicek's laboratory in the Department of Biosystems Engineering, University of Manitoba.

I was involved in all aspects of the research, including ~ 40% of the experimental design, scouting for phosphorus deficient soils around Manitoba, collecting bulk soil samples from fields near Roseisle and Justice, the running of all experiments, laboratory analyses, data processing and statistical analysis, and preparation of thesis chapters. I designed the protocol for the seedling toxicity experiment with help from Drs. Don Flaten and Francis Zvomuya. I also supervised 4 summer students who helped me with the setting up of the experiments, watering, and harvesting.

Also, I designed and conducted an incubation study, which was completed after preparation of this thesis. A manuscript of this experiment, of which I am the principal author, is under preparation and will be submitted to the Journal of Environmental Quality.

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1. INTRODUCTION

1.1 Manure-Recovered Struvite

Phosphorus removal from manure through forced precipitation of struvite or magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4{\cdot}6H_2O$) increases the N:P ratio of the remaining manure (Burns and Moody, 2002). The process has been proven to be feasible and capable of recovering as much as 90% of reactive P (PO_4^{3-}) from animal manures (Beal et al., 1999; Burns and Moody, 2002; Jordaan et al., 2010; Nelson et al., 2003). There has been immense progress made in the struvite precipitation technology, with successful recovery 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). Struvite precipitation is affected by manure Mg^{2+}/PO_4^{3-} and PO_4^{3-}/NH_4^+ ratios, pH, and temperature (Zeng and Li, 2006).

Pure struvite is 44% H_2O, 39% PO_4, 10% Mg and 7% NH_4 by mass (Gell et al., 2011), which corresponds to a nutrient composition of 5.7% N, 12.6% P, and 9.9% Mg (Zeng and Li, 2006). Phosphorus recovery as struvite has generated much interest for environmental reasons due to the slow-release nature of this P form. Struvite has a low water solubility at neutral pH (~0.2 g L^{-1}) (Barak and Stafford, 2006; Shu et al., 2006), and is least soluble between pH 8.9 and 9.25 (Nelson et al., 2003). Results from studies on struvite behavior show that struvite solubility decreases with increasing pH and steadily increases with increasing temperature up to 50^oC, after which it begins to decrease (Aage et al., 1997; Doyle and Parsons, 2002). This low solubility gives struvite slow-release properties, making it a potentially valuable source of P for crops, which can supply P for longer periods, in a more synchronized way, than conventional P forms (Shaviv, 2001).

Proposals for the use of struvite as a potential P-source for crops date back to as early as 1858 (Barak and Stafford, 2006). Numerous studies have reported that struvite is as effective as conventional rapid release P fertilizers in supplying P for corn (Antonini et al., 2012; Barak and Stafford, 2006; Gell et al., 2011), ryegrass (Antonini et al., 2012; Johnston and Richards, 2003; Plaza et al., 2007), spring wheat (Massey et al., 2009), and canola (Ackerman et al., 2013).

1.2 Livestock Manure Management Challenges

There is increasing pressure on agricultural producers to adopt best management practices (BMPs) due to the increasing threat of eutrophication of surface water bodies (Beaulieu, 2004). Eutrophication is mainly attributed to P from sediments deposited in runoff from P-enriched topsoils of agricultural lands constantly receiving high doses of P fertilizers or manures, especially hog manure (Daniel et al., 1998; Flaten, 2006). This is a common problem for lakes such as Lake Winnipeg which receive large amounts of runoff from agricultural fields. According to a survey by Statistics Canada (2013), 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. However, more than 50% of farmers in Canada fail to implement BMPs due to economic pressures (Statistics Canada, 2013), and this aggravates the problem of pollution from agricultural operations.

The major environmental concern with agriculture, especially the land application of manures, emanates from the large nutrient quantities in livestock manure. In 2006, 181 million tonnes of manure were produced in Canada (Statistics Canada, 2009). Most animal manures contain nearly as much P as N, yet plants take up about 2.4 to 4.5 times as much N as P (Mullins, 2009). Consequently, the excess P that remains in soil after manure is applied to meet crop N needs limits the amount that farmers can apply on their farmland. In most cases, farmers have to transport large volumes of manure to distant areas with low soil test P (STP) levels. Therefore, reducing the P levels in manure before the manure is applied to land may facilitate the application of more manure on less land, easing the problem of manure disposal and the environmental risks associated with it. To reduce P loading of agricultural land receiving high doses of manure, farmers can grow high P-demanding crops, such as canola and alfalfa. Some of the strategies for reducing manure P content before land application include the reduction of P in livestock feed, solid-liquid separation, and the recovery of P as struvite.

1.3 Canola Production and its Challenges

Canola *(Brassica spp.),* also known as oilseed rape, is a major crop grown in the Canadian prairies which was bred in the 1960s - 1970s by Canadian scientists Stefansson and Downey (Canola Council of Canada, 2014). The name canola is an abbreviation for "Canadian oil" (Casséus, 2009). Intensive global oilseed rape production emerged during World War II due to the need for effective lubricants (Casséus, 2009), and since then, oilseed production has continued to expand. The expansion has led to canola becoming the second largest oilseed crop globally after soybean (Raymer, 2001). The two main economically important species of canola are *B. napus* and *B. rapa*. In Canada, canola is mainly grown in Saskatchewan, Alberta, Manitoba, and Ontario. Canola has many uses, such as cooking oil and livestock feed for local and international markets. The canola industry employs more than 249,000 Canadians and contributes $19.3 billion annually to the Canadian economy (Canola Council of Canada, 2014).

Current canola varieties are high-yielding and have correspondingly high fertilizer nutrient requirements (Bolland, 1997; Grant and Bailey, 1993; Karamanos et al., 2005). Therefore, canola production success mainly depends on the ability of the soil to meet the crop's nutrient needs. In the Canadian prairies, P is among the most limiting nutrients (Grant and Wu, 2008) and it is routinely applied to optimize crop yield and quality. Phosphorus is required in smaller amounts than N, but is equally critical for optimum crop development, maturity, and seed yield. It plays a vital role as a structural component in nucleic acids, phospholipids and many other cell structures, and is required for energy transfer in metabolism (Elser, 2012). Phosphorus deficiency leads to stunted stem and leaf growth as well as poor root development, which lead to reduced crop vigor, and ultimately, reduced yield and quality (Grant and Bailey, 1993).

Canola generally requires about 25% more P than cereal crops such as wheat (Hocking et al., 1999). However, due to its higher P uptake efficiency (PUE) at low STP levels, canola is able to recover more applied P than other crops to give greater yield responses (Bolland, 1997; Brennan and Bolland, 2001; Brennan and Bolland, 2009). In calcareous soils, canola PUE is enhanced by root proliferation, which allows the plant to effectively explore a larger soil volume, and the exudation of organic anions into the rhizosphere, which increases plant availability of P fixed in Ca and Mg phosphates (Pearse et al., 2006; Shenoy and Kalagudi, 2005; Vance, 2008). Malhi et al. (2011) measured significantly lower STP concentrations in the 0- to 15-cm soil layer following canola harvest as compared to wheat harvest in a canola-wheat rotation. Growing canola in rotation with crops with lower PUEs can help rejuvenate the soil and obviate continuous application of high rates of fertilizers.

Proper choice of P application rates and placement methods can help improve P use efficiency in crop production, which remains a major challenge for agriculture (Dobermann, 2007; Schröder et al., 2011). Applying P in the canola seedrow where developing roots can easily access it optimizes PUE and ensures adequate P supply from early stages of plant growth (Grant and Wu, 2008; Karamanos et al., 2002). However, seedrow placement of high rates of conventional soluble P fertilizers, such as MAP, can also increase seedling toxicity (Canola Council of Canada, 2014), hence the need for alternative P-sources which can be applied in the seedrow with lower risks of seedling toxicity. At P rates above the threshold for seedling toxicity, sidebanding of highly-soluble P fertilizers is the most efficient placement method (Binford, 2006; Flaten et al., 2003).

1.4 Conventional Phosphorus Fertilizers

Seventy five percent of Canadian crop producers use fertilizers, with about 90% of the fertilizers applied in the spring (Korol, 2004). As of 2011, commercial fertilizers were applied on 21.1 million hectares of land in the Canadian prairies, which is about 84% of the 25 million ha receiving commercial fertilizers in Canada (Statistics Canada, 2012). Most conventional P fertilizers are prepared by reacting phosphate rock with sulfuric acid to produce phosphoric acid, which is then further processed to different forms of soluble fertilizers (Binford, 2006). However, there is growing concern over the accumulation of large quantities of P in surface water bodies receiving runoff from P-enriched topsoils in agricultural fields. Also, there is a pollution risk from heavy metal contaminants, such as uranium and cadmium, associated with the use of P fertilizers of rock phosphate origin (Kratz and Schnug, 2006; Mclaughlin et al., 1996).

Monoammonium phosphate ($NH_4H_2PO_4$) (11-52-0) is the most commonly used P fertilizer in the Canadian prairies (Canola Council of Canada, 2014; Grant and Wu, 2008; Statistics Canada, 2008). It is a dry, high analysis granular fertilizer sourced from phosphate rock. Monoammonium phosphate is a highly soluble (85% water-soluble and 100% citrate-soluble) (Chien et al., 2011) and readily plant-available source of P and N (Binford, 2006). In the 2013/2014 season, 210,000 metric tonnes of MAP were shipped to the Canadian market, with 56% of this going to the prairie provinces (Statistics Canada, 2014a).

Although MAP has a low toxicity index because it produces less ammonia relative to most ammonium-producing fertilizers (Rader et al., 1943), over-application in contact with seeds poses the risk of salt toxicity, reducing seed germination and increasing seedling mortality (Canola Council of Canada, 2014). Crops differ in their tolerance to seedrow placed P, for instance, canola is less tolerant than wheat (Qian and Schoenau, 2010a). Field tests on four different soils from the Canadian prairies showed that seedrow placement resulted in reduced canola plant density relative to sidebanding, although seed yield and N uptake were higher for seedrow placed MAP (Lemke et al., 2009).

1.5 Soil Phosphorus Fertility

Soil P exists in various chemical forms, broadly classified as inorganic P (P_i) and organic P (P_o). Plants absorb P_i that is dissolved in the soil solution. The plant available form of P_i in the soil solution is the primary orthophosphate anion ($H_2PO_4^-$), with smaller amounts of the secondary orthophosphate anion (HPO_4^{2-}) (Mullins, 2009). However, the predominant ionic form of P_i in the soil solution is pH-dependent. In soils with pH values greater than 7.2, the HPO_4^{2-} form predominates, while in soils with a pH between 5.0 and 7.2, $H_2PO_4^-$ is the predominant form (Mullins and Hansen, 2006).

Phosphorus is relatively immobile in soil, moving predominantly by diffusion (Syers et al., 2008). The rate of P diffusion is, however, very slow, ranging from about 10^{-12} to 10^{-15} m^2 s^{-1} (Schachtman et al., 1998), moving overall distances as small as 6.4 mm (Mullins, 2009; Mullins and Hansen, 2006). Due to this, most applied P persists near the site of fertilizer placement (Grant et al., 2009), and when placed away from the seeds, remains unavailable for plant uptake because it may not make it to the root zone (Mullins and Hansen, 2006). Moreover, diffusion rates are slower at low temperatures, such as those early in the growing season in the prairies (Karamanos et al., 2002). This limited mobility of P in prairie soils is a major challenge in canola production.

Although total soil P usually ranges from 900 to 1,800 kg P ha^{-1} of topsoil (0- to 15-cm layer) (Mullins, 2009), the bulk of this P is unavailable to plants because the P_i in the soil solution of most agricultural soils ranges from only <0.01 to 1 mg P kg^{-1} soil (Mullins and Hansen, 2006). The processes of adsorption/desorption, precipitation/dissolution, oxidation/reduction and mineralization/immobilization control P transformations in soil (Azeez and Van Averbeke, 2010; McLaughlin et al., 2011). Most of the P transformations in soil are highly influenced by P_i concentration (Shaviv, 2001). Mathematical models suggest that changes in soluble P concentrations following P application may be estimated from concurrent equilibrium reactions of adsorption-desorption, precipitation-dissolution, and ion pairing (Grant and Heaney, 1997). Adsorption, precipitation, and immobilization compete with crop P uptake by removing P_i from the soil solution.

In acid soils, P_i is mostly fixed due to precipitation reactions with Fe and Al while in alkaline soils P_i precipitates with Ca to form phosphates with very low solubilities and plant availabilities. For instance, the P retention capacity of alkaline Manitoba soils has been reported to be significantly influenced by exchangeable Ca and Mg and the textural composition of the soil (Ige et al., 2005). On the other hand, plant availability of P_o is highly dependent on mineralization rates, hence the usual need to supplement soil P with inorganic fertilizers.

According to Dobermann (2007), most agricultural crops recover only 20 to 30% of applied P during their growth cycles under favorable growth conditions, while much of the remainder accumulates in the soil and is eventually recovered by subsequent crops over time. Proper fertilizer P management is critical for optimizing crop production potential while minimizing P losses to maintain good environmental stewardship (Roberts, 2007). The amount of P available for plant uptake generally depends on the P fertilizer rate, which varies with fertilizer type, placement method, and prevailing soil conditions. The amount of P taken up by a plant from a single fertilizer application is influenced by soil P concentration and the P-buffer capacity of the soil (Syers et al., 2008; Yerokun and Christenson, 1990)

1.6 Slow-Release Phosphorus Sources

One option to increase yields and improve P use efficiency, while addressing the negative environmental impacts that arise from the use of fertilizer P, is to control the release of P from fertilizers and manures (Du et al., 2006; Oertli, 1980). This can be achieved through the use of slow-release fertilizers (SRFs) (Burns and Moody, 2002).

Slow-release P fertilizers are fertilizers from which P release into the soil or other growth medium occurs in a relatively more controlled manner and at a slower rate than conventional fertilizers (Shaviv and Mikkelsen, 1993). They contain P in forms which either delay its release for plant uptake and use after application or which make it available to the plant significantly longer than a reference rapidly-available P fertilizer (Trenkel, 1997). Slow-release P fertilizers can be classified into various groups depending on their chemical and structural nature or mode of action (Shaviv, 2001; Shaviv and Mikkelsen, 1993). For instance, struvite releases P through low solubility while others release P through coated surfaces (e.g., CMAP) (Trenkel, 1997).

1.6.1 Polymer-Coated Monoammonium Phosphate

There is increasing awareness of the potential benefits of using SRFs to reduce environmental hazards as well as to improve and maintain nutrient-use efficiency (Chien et al., 2009). It is generally expected that SRFs can meet crop nutrient demands for the entire season through single applications (Davidson and Gu, 2011; Shaviv, 2001; Song et al., 2014; Trenkel, 2010). However, there is still limited use of polymer-coated P fertilizers in canola and wheat production due to inadequate availability, scanty details of application and benefits in the farming community, and their high costs, which range between 4 to 8 times that of their conventional fertilizer equivalents (Grant and Wu, 2008; Shu et al., 2006; Trenkel, 2010).

Various polymers are used as coatings in SRFs (Trenkel, 1997) and the variations in the properties of these polymers are useful in determining the specific characteristics and behavior of coated SRFs (Hanafi et al., 2000; Shaviv et al., 2003). Most models for the prediction of P release from CMAP emphasize the importance of granule radius and coating thickness and the interrelationships between temperature, water, and nutrient permeability (Shaviv, 2001; Shaviv et al., 2003). Phosphorus release from CMAP occurs slowly through the coating or through cracks and pinholes after partial decomposition of the coating (Shaviv, 2001). Release occurs by diffusion down a concentration gradient or by mass flow down a pressure gradient or by a combination of both (Du et al., 2006; Shaviv, 2001).

Water vapor penetrates the coating of the CMAP granule and condenses on the solid core containing the P, dissolving part of the P and causing a build-up of internal pressure. Phosphorus release then occurs by diffusion down a concentration gradient across the coating (Shaviv, 2001). For any single granule, the diffusion mechanism results in a gradual, sigmoidal P-release curve (Shaviv, 2001). However, if the internal pressure exceeds the membrane resistance, the coat will rupture and P will be released instantaneously (Oertli, 1980). This rapid release may lead to seedling toxicity if high fertilizer rates are applied close to seeds.

In a study to evaluate the concept of polymer-coated fertilizers, Pauly et al. (2001) found that, compared to uncoated MAP, CMAP improved the growth, P uptake and PUE of barley (Pauly et al., 2002). In another study, Qian and Schoenau (2010a) also observed that, compared to conventional MAP fertilizer, CMAP greatly increased the tolerance of wheat, canola and other crops to higher rates of seedrow-placed P due to delayed P release. However, some drawbacks of using CMAP are (1) the possibility of release which is too slow for plant demand, (2) high production costs, (3) the potential accumulation of synthetic materials from the coating (Trenkel, 1997), and (4) the risk of toxicity if the diffusion mechanism fails.

Unlike CMAP, struvite is not a coated SRF, and, therefore, does not pose some of the challenges associated with CMAP. Additionally, struvite recovery is a way of recycling P on hog farms, which may reduce the continued application of commercial fertilizers and reduce P loss to the environment. The environmental benefits from improved hog manure P management and the potential agronomic benefits from the use of struvite as a P fertilizer may eventually contribute to the sustainability of agriculture.

1.7 Thesis Rationale

The main objective of this thesis research was to determine the agronomic effectiveness of hog manure-recovered struvite as a P-source for canola, relative to the commercial fertilizers, MAP and CMAP. In Chapter 2, results from a greenhouse bioassay evaluating the effectiveness of differential rates and placement methods of struvite on canola and spring wheat DMY and P use efficiency indices are presented. Struvite is a promising option to recover, reduce, and recycle manure P before land application of manure. However, little is known about the agronomic effectiveness of the recovered struvite on economically important annual crops such as canola and wheat. Due to the slow-release properties of struvite, the longevity of P supply from struvite relative to the commercial sources was explored by growing three phases of canola and wheat. Improving the P status of P-deficient soils is a priority for prairie agriculture, and SRFs such as struvite may provide an option to maintain P use efficiency while enhancing soil P status.

The effect of seed-placed recovered struvite, relative to MAP and CMAP, on canola seedling toxicity was investigated at different P rates in a separate growth room experiment (Chapter 3). The potential effects of seedrow placed SRFs in general on crop injury are not well-documented (Qian and Schoenau, 2010a). High rates of CMAP have been reported to be safe in the seedrow of sensitive crops, but no studies have assessed struvite seedling toxicity. If the release of P from struvite is slow enough to make it safe for application at high rates, then struvite could be a better alternative to MAP for canola. However, it is also important not to compromise P supply by release which is too slow or too delayed.

A primary hypothesis of this thesis research is that the slow-release properties of struvite and CMAP will minimize seedling toxicity in canola production while supplying adequate P and enhancing DMY and PUE in canola and spring wheat.

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2. HOG MANURE-RECOVERED STRUVITE AS A PHOSPHORUS FERTILIZER FOR CANOLA AND WHEAT: EFFECTS ON BIOMASS YIELD AND PHOSPHORUS USE EFFICIENCIES

2.1 Abstract

Recovery of manure phosphorus (P) as magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4 \cdot 6H_2O$), commonly known as struvite, is one option to mitigate the risk of P contamination of surface water bodies from hog operations. The slow release of P from recovered struvite may help improve crop P use efficiency. This greenhouse bioassay evaluated the agronomic effectiveness of liquid hog manure-recovered struvite relative to monoammonium phosphate (MAP) and polymer-coated MAP (CMAP). Struvite and the MAPs were evaluated on canola *(Brassica spp.)* grown in rotation with wheat (*Triticum aestivum*) in two low soil test P (STP) (Olsen P < 6 mg kg^{-1}) soils: a sandy Gleyed Regosol (Entisol) and a clay loamy Orthic Black Chernozem (Udic Boroll). The fertilizers were applied either in the seedrow or in a sideband 2.5 cm below and besides the seedrow at 7.5 and 15 mg P kg^{-1} rates, which correspond to 25 and 50 kg P_2O_5 ha^{-1}, respectively. In both soils, struvite produced canola and wheat dry matter yield (DMY), P uptake efficiency (PUE), and agronomic efficiency (AE) that were not significantly different from those of MAP and CMAP in the first crop phase. However, at the 15 mg P kg^{-1} rate applied to canola, struvite out-yielded MAP in the second phase and both MAP and CMAP in the third phase. Overall, these results indicate that, despite the documented slow release properties of struvites in general, struvite recovered from liquid hog manure can supply sufficient P to sustain yields and P use efficiency matching those for MAP.

2.2 Introduction

Intensive hog production in western Canada generates large volumes of manure daily, with annual production estimated at >16 million tonnes (Hofmann, 2013). Manitoba, which has the third largest hog population (2.8 million as of January 2014) of all Canadian provinces (12.7 million), accounts for about 20% of daily hog manure output (Statistics Canada, 2014b).

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 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) and repeated manure applications based on crop N needs can result in excessive 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 manures 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 P as struvite [magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4 \cdot 6H_2O$)] prior to land application of manure. Pure struvite has an elemental composition of 5.7% N, 12.6% P, and 9.9% Mg. Immense 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), and swine manure (Jordaan et al., 2010). The higher N:P ratio of manure following recovery of struvite allows the 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, 2008). Monoammonium phosphate is the most commonly used P fertilizer on the Canadian prairies. In the 2013/2014 season, 2×10^5 metric tons of MAP were shipped to the Canadian market, with 56% of this going to the prairies (Statistics Canada, 2014a). 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 (Barak and Stafford, 2006; Gell et al., 2011). When compared with monocalcium phosphate, it gave similar ryegrass DMY in sandy clay loams 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 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 supplying P to ryegrass. Similarly, wastewater-derived struvites gave similar spring wheat DMY to triple superphosphate fertilizer in slightly acidic (pH 6.5) and alkaline (pH 7.6) soils (Massey et al., 2009).

However, there is a dearth of information on the agronomic performance of hog manure-recovered struvite on high P-demand crops such as canola, which is also sensitive to high rates of seed row-placed soluble P fertilizers. Due to its low solubility (Barak and Stafford, 2006; Nelson et al., 2003), hence more gradual release of P compared with conventional fertilizers, struvite qualifies as a slow-release fertilizer (Shaviv, 2001). It could conceivably allow seed row application of P at higher rates than currently feasible with conventional fertilizers such as MAP without causing toxicity to canola seedlings. Recently, there has been growing interest in more efficient fertilizer forms, particularly controlled- or slow-release fertilizers, because of increasing awareness of their potential to minimize environmental hazards and to improve and maintain nutrient use efficiency (Shaviv and Mikkelsen, 1993).

The overall objective of this study was to evaluate the agronomic value of liquid hog manure-recovered struvite in canola production in P-deficient calcareous soils. Specifically, we compared the effects of differential rates of seedrow placed or sidebanded struvite, MAP, and CMAP on early season above-ground DMY and P efficiency indices.

2.3 Materials and Methods

2.3.1 Hog Manure Recovered Struvite

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). The resulting sludge was air-dried and then finely-ground prior to storage. For consistency of P-source application, reverse osmosis (RO) water was added to moisten the finely-ground struvite, forming a paste that was then dried and cut into uniform granules similar in size to those of MAP (11-52-0).

2.3.2 Soils

The two soils (0- to 15-cm layer) used in this greenhouse bioassay were a dark-grey, sandy Gleyed Regosol (Entisol) from Roseisle (N 49^o 33.577′; W 098^o 24.824′) and a clay loamy Orthic Black Chernozem (Udic Boroll) from Justice (N 49^o 58.590′; W 099^o 52.908′), Manitoba, Canada.

2.3.3 Laboratory Analysis

2.3.3.1 Recovered Struvite and Soils. Recovered struvite was analyzed for total N using a Vario Max Elementar combustion analyzer (Elementar Analysensysteme GmbH, Donaustrasse, Germany). Ammonium N concentration in the struvite was determined with a Timberline ammonium analyzer (Timberline Instruments, Boulder, Colorado) following extraction with 2 M KCl [1:10 struvite (dry wt.):solution ratio] (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 ICP (Perkin Elmer, Waltham, Massachusetts) following digestion with $HNO_3/H_2O_2/HCl$ according to a modified USEPA Method 3050B (USEPA, 1996). Struvite pH was determined in a 1:1 struvite: water suspension.

Plant available (Olsen) P in soil 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 of 5 g of soil with 50 mL of 0.5 M $NaHCO_3$ at a pH of 8.5 (Olsen et al., 1954). Nitrate N concentration in the soil was determined by the Cd reduction method following extraction with 10 mL of 2 M KCl per gram of soil (Mulvaney, 1996). Calcium and Mg were determined by ICP-OES following extraction of 5 g of soil with 33 mL ammonium acetate at pH 7. Soil particle size analysis was measured using the hydrometer method (Gee and Or, 2002). Electrical conductivity and pH were measured in a 1:1 soil: water suspension. Soil organic matter concentration was determined using the loss on ignition method (Nelson and Sommers, 1996).

2.3.3.2 Plant Tissue. Total P in plant tissue was analyzed with ICP-OES (Thermo iCAP 6300 Radial, Thermo Electron Corporation, Cambridge, UK) following digestion of 0.5 g of ground plant tissue with 10 mL concentrated HNO_3 at 175°C for 15 min using a MARS 5 microwave system (CEM Corporation, Matthews, NC).

2.3.4 Experiment Setup

The experiment was laid out in a randomized complete block design with a factorial + 2 controls treatment structure and three replicates. A factorial combination of P-source (struvite, MAP and CMAP), P rate (7.5 and 15 mg P kg^{-1}, which correspond to 25 and 50 kg P_2O_5 ha^{-1}, respectively), placement method (seed row and sideband), and soil type (clay loam and sand) was used. Unfertilized soils (controls) were included for comparison. 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 over three crop phases. The canola-wheat rotation was chosen to reflect common practice on canola farms in the Canadian prairies.

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 content to 260 g kg^{-1} in the sand and 390 g kg^{-1} in 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 m^{-2} for canola and 362 plants m^{-2} for wheat. Struvite (5.7-23-0.4), MAP (11-52-0) and CMAP (11-52-0) were applied to the potted soils at the rates indicated above. The lower rate (7.5 mg P kg^{-1} soil) corresponds to the maximum MAP rate (22-28 kg P_2O_5 ha^{-1}) currently recommended to minimize seedling toxicity for seed-placed P for canola whereas the rate (15 mg P kg^{-1} soil) reflects the P requirements of canola (50 kg P_2O_5 ha^{-1}) (Thomas, 2014). The fertilizers were placed either with the seed (seedrow placement) or 2.5 cm beside and below the seedrow (sidebanding) in 2.5-cm wide bands across the center of each pot.

The weight of each pot after initial watering (as described above) 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.

2.3.5 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). Canola seed yield is highly and positively correlated with dry matter yield (Campbell and Kondra, 1978). Maximum biomass accumulation and P uptake rates occur at 21-42 DAE (Malhi et al., 2007). The plants were cut using clippers at approximately 2.5 cm above the soil surface. Harvested above-ground biomass was dried at 60°C for 48 h and weighed 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 prior to laboratory analysis. Roots were chopped and mixed back into 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, giving a rate of 5 mg Cu kg^{-1}. This was necessary to prevent Cu deficiency symptoms 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 apiece of canola and wheat, with 14-d fallow periods allowed between successive crops. After planting, soils were watered with a nutrient solution containing nutrients other than P and Cu at 50% of the concentration added at the first planting. Reverse osmosis water was added to bring the moisture content to the same level as in the first crop phase.

2.3.6 Calculations

Phosphorus uptake (PU, mg P kg^{-1} soil) 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. The assumptions when using the difference method are that P uptake and yield in the fertilized soils is solely dependent on the applied P and not on the soil P reserves, and that the enhanced plant vigor from the added P fertilizer does not significantly enhance P uptake and utilization from soil P reserves, which remain similar to those in the unfertilized soils (Syers et al., 2008).

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

$$\text{Cumulative PU} = PU_1 + PU_2 + PU_3 \qquad [4]$$

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

2.3.7 Statistical Analyses

A repeated measures analysis of variance (ANOVA) was performed using the GLIMMIX procedure of SAS (SAS Institute, 2014). 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 (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: compound symmetry for canola DMY, PU, PUE, and wheat PUE; unstructured for wheat DMY and residual Olsen P after canola harvest; heterogeneous autoregressive for canola AE and wheat PU; and heterogeneous compound symmetry for wheat AE and residual Olsen P after wheat harvest. Treatment effects were considered significant when $P < 0.05$. The Tukey-Kramer multiple comparison procedure was used to compare treatment means. Cumulative P uptake and PUE data were also analyzed using the GLIMMIX procedure, with crop sequence, soil, P-source, P rate, and placement method as fixed effects while block was a random effect.

2.4 Results

2.4.1 Recovered Struvite Properties

Recovered struvite had a pH of 5.5 and contained 100 g P kg^{-1} and 57 g TN kg^{-1} (Table 2.1). 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). Based on its Mg concentration, the maximum purity of the recovered struvite was approximately 65%, with an 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 P forms.

Table 2.1 Selected chemical properties of hog manure recovered struvite and commercial fertilizers used in the greenhouse bioassay

Analyte	Struvite	MAP	CMAP
	g kg^{-1} (a ir-dry basis)		
Total N	57.7	110	110
Ammonium N	16	110	110
Total P	100.5	227	227
K	3.7	-	-
Ca	5	-	-
Mg	64	-	-
pH	5.5	4.8	4.8
Moisture (g kg^{-1})	400	12	12

†MAP, monoammonium phosphate (11-52-0); CMAP, polymer-coated MAP

2.4.2 Soil Properties

Selected properties of the soils used in the bioassay are presented in Table 2.2. 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 (≤ 10 mg P kg^{-1}) for canola and wheat. The clay loam had higher CEC, OC content, EC, field moisture capacity and, Ca and Mg concentrations.

Table 2.2 Selected chemical and physical properties of soils used in the experiments

Nutrient/Parameter	Sand	Clay loam
Nitrate (kg ha^{-1})	5.9	27
Olsen P (mg kg^{-1})	3.5	5.5
Mg (mg kg^{-1})	192	907
Ca (mg kg^{-1})	2348	3823
K (mg kg^{-1})	49	203
Chloride (kg ha^{-1})	52	5.5
S (kg ha^{-1})	15	15
B (mg kg^{-1})	0.5	1
Zn (mg kg^{-1})	1.2	0.8
Fe (mg kg^{-1})	15	19
Mn (mg kg^{-1})	2.1	5.3
Cu (mg kg^{-1})	0.3	1.0
Na (mg kg^{-1})	24	17
Organic C (g kg^{-1})	0.9	3.4
Carbonate (%)	0.4	0.4
EC (dS m^{-1})	0.2	0.4
pH	7.95	7.6
CEC ($cmol_c$ kg^{-1})	14	27
Field capacity moisture (kg kg^{-1})	0.1	0.3
Base saturation (%)		
Ca	86.6	70.1
Mg	11.8	27.8
K	0.9	1.9
Na	0.8	0.3

2.4.3 Dry Matter Yield

2.4.3.1 Canola. In the first crop after P application (that is, the first crop phase in the canola-wheat-canola sequence), there were significant ($P < 0.001$) canola DMY responses to P fertilization in both soils. In the second crop phase, all struvite treatments, seed-placed MAP and CMAP at 15 mg P kg^{-1}, MAP sidebanded at 15 mg P kg^{-1}, and CMAP sidebanded at 7.5 mg P kg^{-1} produced significant responses in the clay loam. In the third crop phase, significant responses to seed-placed and sidebanded 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 (Table AII.1).

Analysis of variance of DMY data from a factorial combination of treatments (excluding the controls) showed a significant ($P = 0.004$) P-source × crop phase interaction (Table 2.3). While canola DMY did not differ significantly among P-sources in the first crop phase, struvite significantly outyielded MAP in the second phase and both MAP and CMAP in the third phase (Figure 2.1). Overall, DMY significantly declined with each subsequent phase for all P-sources.

Table 2.3 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	2.4	1.9	5.9	4.7	42.8	16.9	0.15	0.06
2	1.8	1.5	3. 6	3.0	13.4	8.3	0.06	0.01
3	1.2	1.4	1.9	2.7	4.3	7.6	0.03	0.03
P-source (P)								
CMAP	1.7	1.6	3.7	3.6	19.7	12.4	0.07	0.03
MAP	1.8	1.6	3.8	3.6	20.0	11.5	0.08	0.04
Struvite	1.9	1.6	4.0	3.3	20.8	8.9	0.09	0.03
Rate (R)								
7.5 mg P kg^{-1}	1.7	1.5	3.3	3.2	21.8	11.5	0.09	0.03
15 mg P kg^{-1}	1.9	1. 7	4.3	3. 8	18.6	10.3	0.07	0.03
Placement (Ap)								
Seedrow	1.8	1.6	3.8	3.5	20.4	10.4	0.08	0.03
Sideband	1.8	1. 6	3.8	3. 5	20.0	11.4	0.08	0.03
Soil (S)								
Clay loam	1.8	1.8	3.6	4.1	23.3	11.2	0.10	0.03
Sand	1.8	1.3	4.0	2.8	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
P × R	0.04	0.70	0.52	0.84	1.00	0.61	0.48	0.47
P × S	0.07	0.50	0.14	0.58	0.01	0.56	0.53	0.92
R × C	0.03	0.86	< 0.001	0.02	0.001	0.54	< 0.001	0.049
R × S	0.01	1.00	0.37	0.06	0.52	0.10	0.55	1.00
Ap × C	0.001	0.13	0.81	0.73	0.65	0.46	0.001	0.22
S × C	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.002
P × S × C	0.24	0.01	0.69	0.45	0.42	0.73	0.69	0.29
R × S × C	0.001	0.61	0.01	0.67	0.67	0.01	0.03	0.39

† Two-, 3-, 4-, and 5-way interactions with P values > 0.1 for all parameters are not presented.

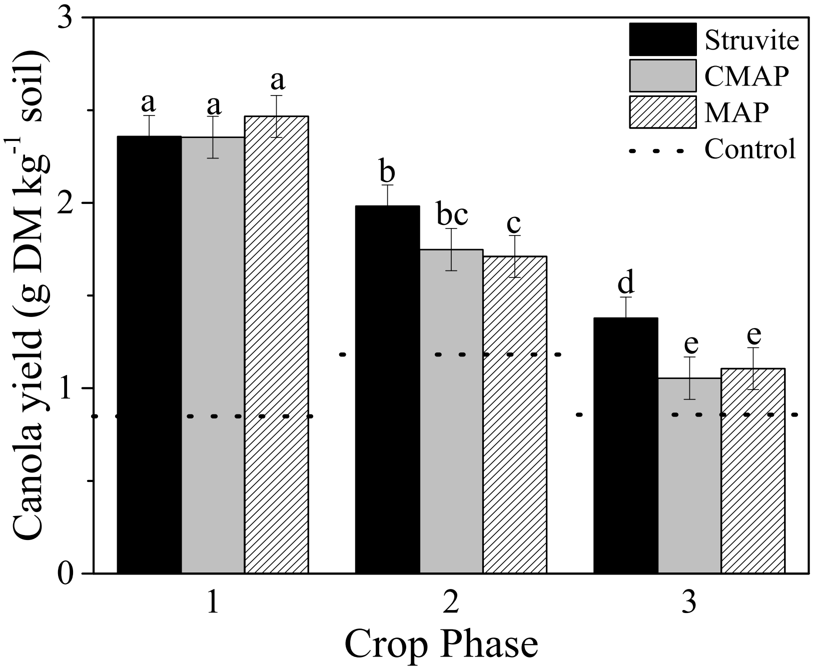

Figure 2.1 Canola dry matter yield as affected by P-sources in the 3 crop phases. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

There was also a significant P-source × rate interaction ($P = 0.04$) for canola DMY, averaged across all crop phases (Table 2.3). 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 2.2). 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.

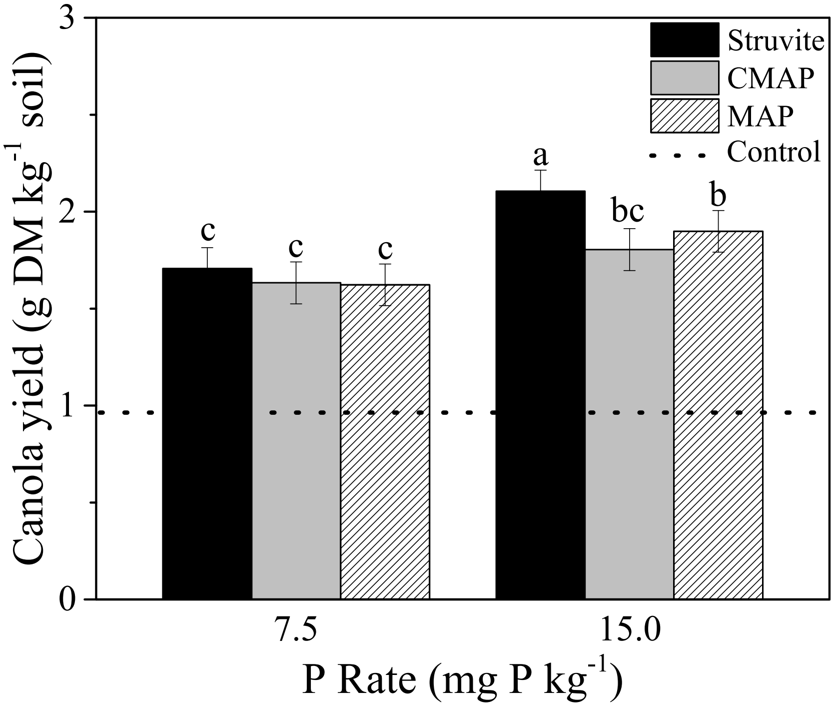

Figure 2.2 Effects of P-source and rate on canola dry matter yield. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

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 2.3). 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 (Figure 2.3). 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.

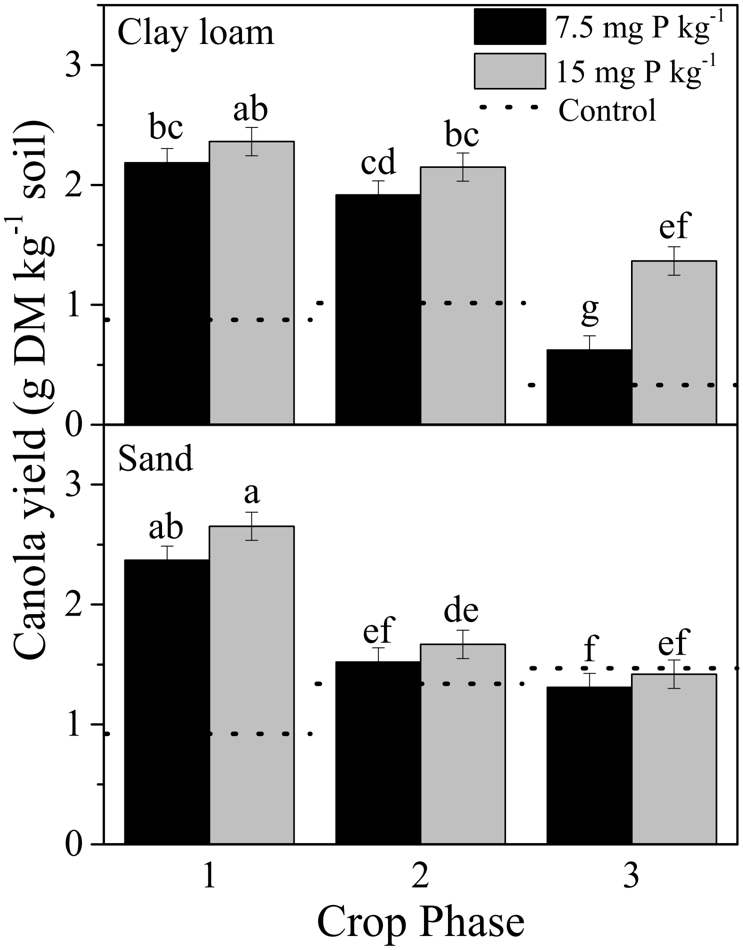

Figure 2.3 Changes in canola biomass yield over three crop phases as affected by P application rate. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

Phosphorus placement method effects varied significantly with crop phase ($P = 0.001$). In the first phase, seedrow placement produced significantly greater DMY than sidebanding, but no significant differences were observed in the second and third phases (Figure 2.4).

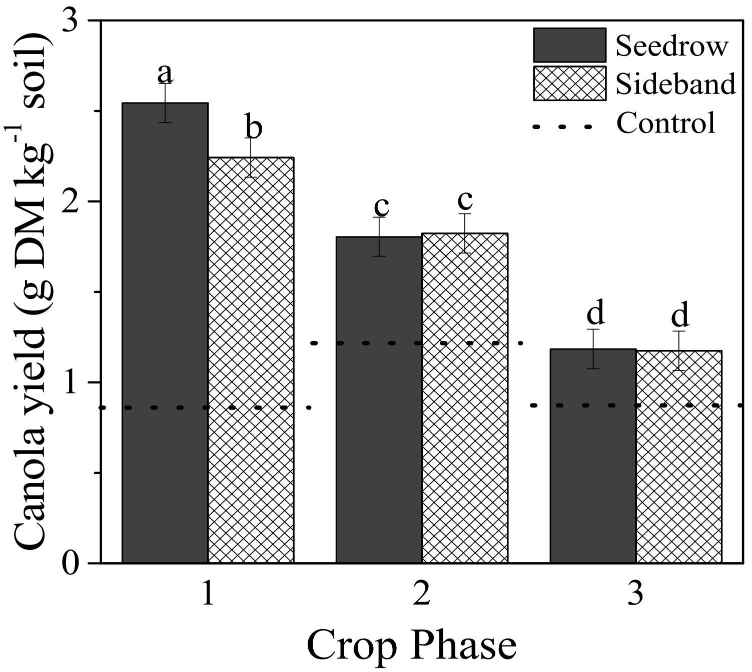

Figure 2.4 Effects of P placement on canola DMY over 3 crop phases. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

2.4.3.2 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 the second and third phases, there were no significant DMY responses to all treatments in both soils (Table AII.1).

For the fertilized treatments (i.e., factorial component), wheat DMY significantly varied with P rate (Table 2.3). 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 2.5). 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.

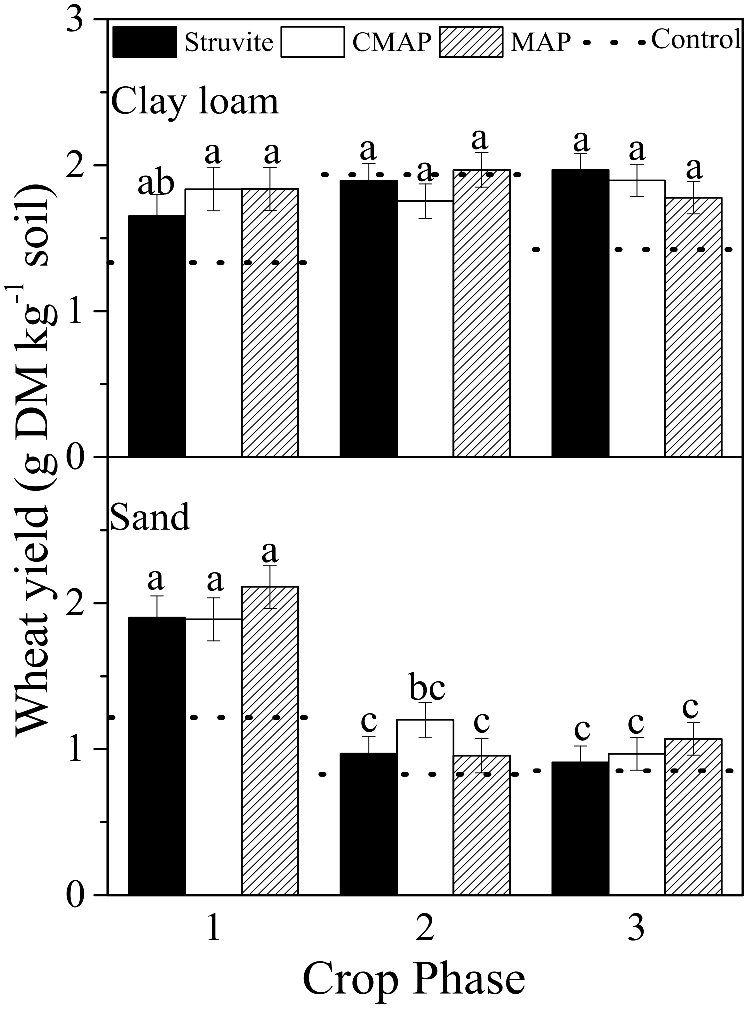

Figure 2.5 Wheat DMY as affected by P-source and soil over 3 growth phases. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

2.4.4 Phosphorus Uptake

2.4.4.1 Canola. In the first phase, P uptake (averaged across soils, placement methods, and rates) was significantly greater in P-fertilized soils than in the controls. However, there were no further responses in P uptake to P application in the second and third crop phases (Table AII.2).

Analysis of variance of data excluding the controls showed a significant rate × soil × crop phase interaction on P uptake by canola (Table 2.3). 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 crop phase in both soils. However, no significant differences were observed in subsequent crop phases (Figure 2.6). 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.

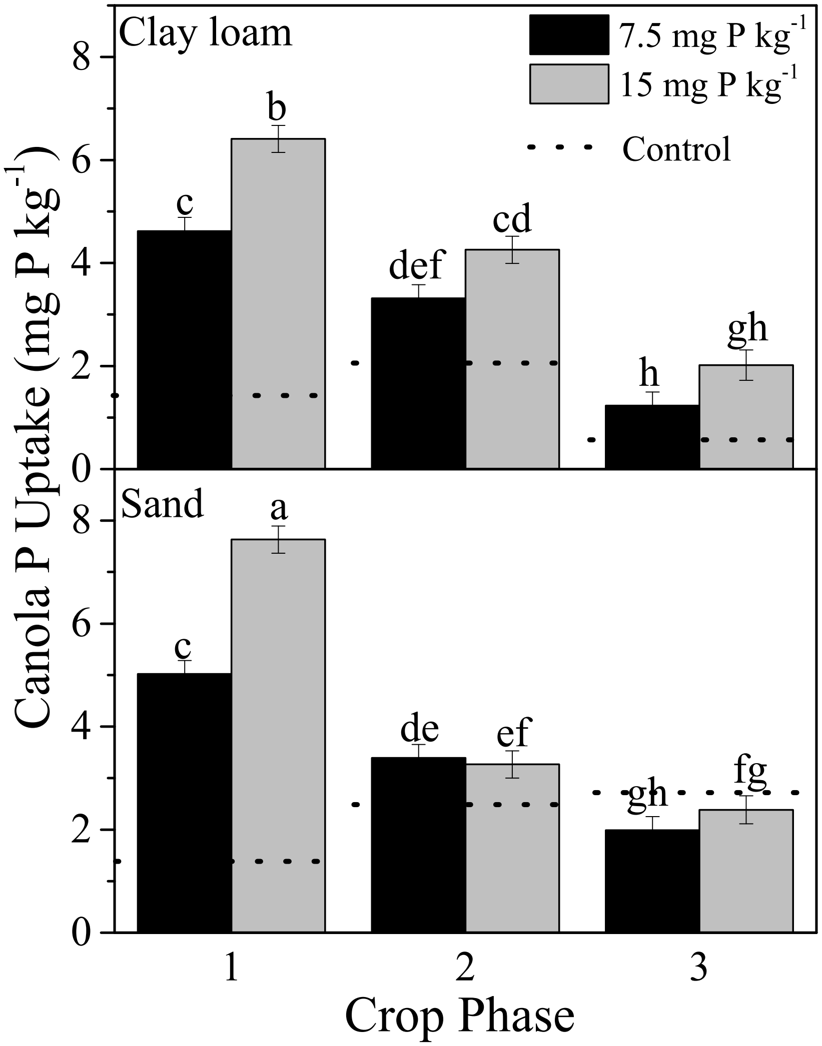

Figure 2.6 Effects of P rate and soil on canola P uptake over three crop phases. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

2.4.4.2 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} (5.9 g mg^{-1}) in the sand relative to the control (1.8 g mg^{-1}). However, no significant responses were observed for CMAP and struvite in this soil, or from all treatments in the clay loam in this phase. Also, none of the treatments significantly increased wheat P uptake relative to the controls in both soils in the second and third crop phases (Table AII.2).

For the factorial component, P-source effects on wheat P uptake were significant but varied with crop phase, as indicated by the significant ($P = 0.01$) P-source × crop phase interaction (Table 2.3). 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 2.7a). By comparison, P-source differences were not significant in the second and third phases.

There was a significant rate × crop phase interaction ($P = 0.02$) for P uptake (Table 2.3). 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 2.7b). However, the rates were not significantly different in the second and third phases.

There was also a significant soil × crop phase interaction ($P < 0.001$) on wheat P uptake (Table 2.3). Phosphorus uptake was significantly greater in the clay loam than in the sand in the second and third phases, but there was no significant difference between the soils in the first phase (Figure 2.7c). Overall, wheat P uptake significantly declined in the second phase relative to the first phase, but there was no significant decline in the third phase.

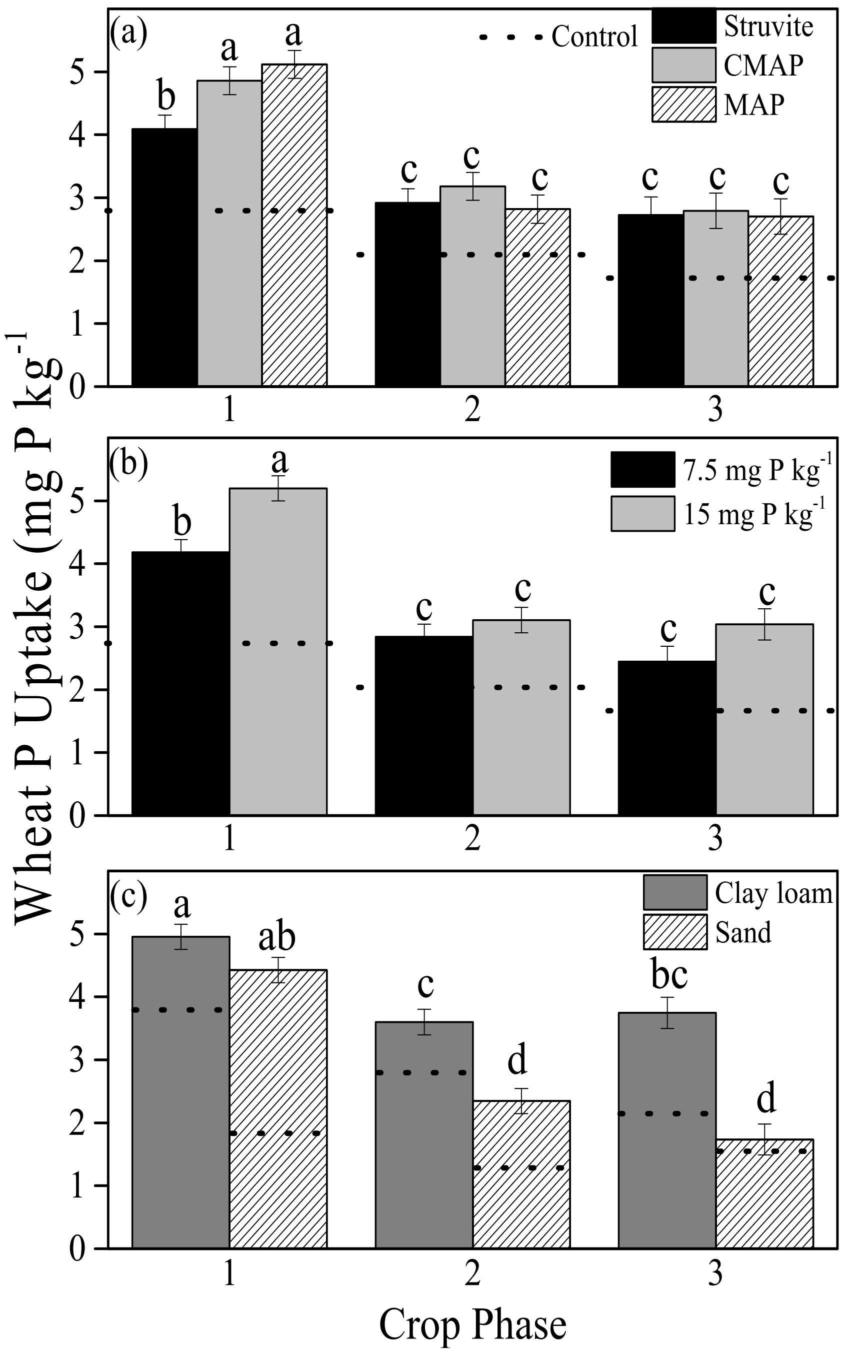

Figure 2.7 Effects of; (a) P-source, (b) P rate, and (c) soil type on wheat P uptake over 3 growth phases. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

2.4.5 Phosphorus Uptake Efficiency

2.4.5.1 Canola. There was a significant P-source × soil interaction (P = 0.01) for PUE of canola averaged across phases. Struvite and CMAP produced significantly greater PUE in the clay loam than in the sand (Figure 2.8). 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.

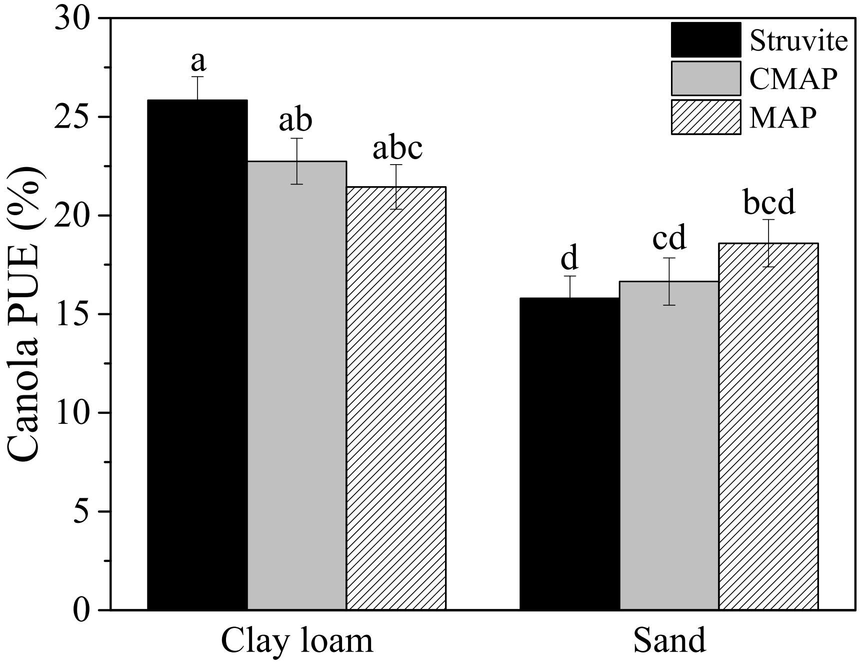

Figure 2.8 Phosphorus uptake efficiency (PUE) of canola as affected by P-source and soil type. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure (P > 0.05). Error bars represent standard errors of the least squares means.

There was also a significant rate × phase interaction (P = 0.001) (Table 2.3). 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 2.9). By comparison, no significant differences were detected between the rates in the second (mean PUE = 14%) and third (4%) crop phases.

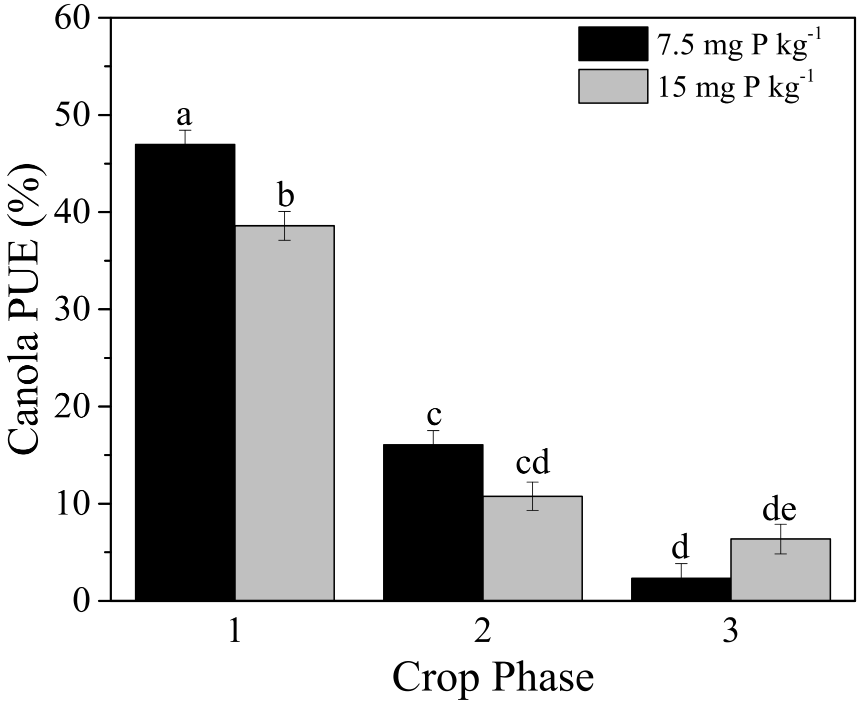

Figure 2.9 Phosphorus uptake efficiency (PUE) of canola as affected by P rate and crop phase. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

There was a significant soil × phase effect ($P < 0.001$) for PUE (Table 2.3). The PUE of canola was significantly greater in the sand (46%) than in the clay loam (40%) in the first phase (Figure 2.10). 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).

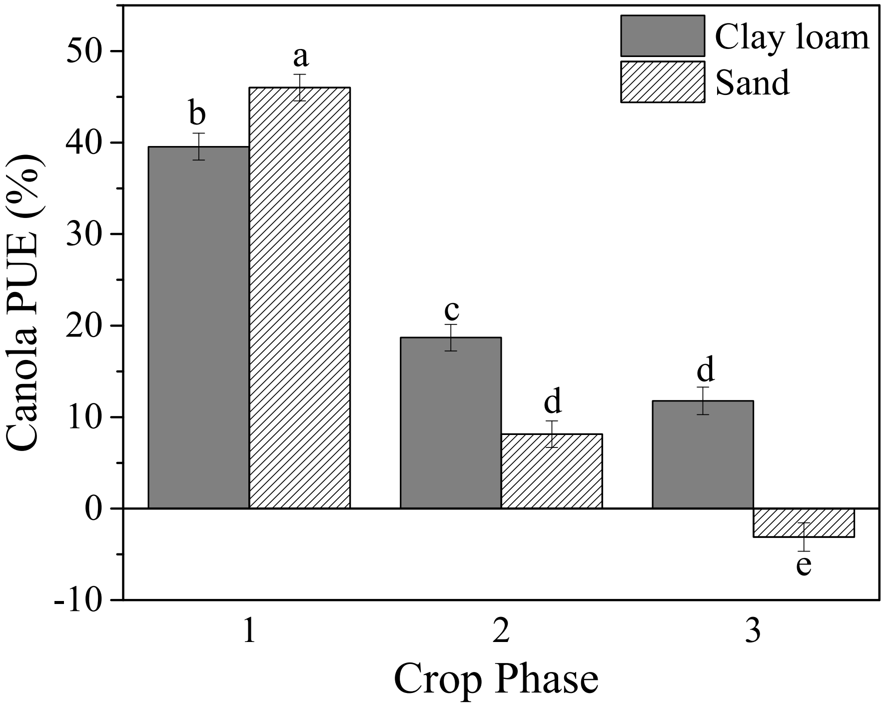

Figure 2.10 Phosphorus uptake efficiency (PUE) of canola as affected by soil and crop phase. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure (P > 0.05). Error bars represent standard errors of the least squares means.

2.4.5.2 Wheat. There was a significant rate × soil × phase interaction ($P = 0.01$) for PUE of wheat (Table 2.3). In the first phase, PUE at the 7.5 mg kg-1 rate was significantly greater in the sand (27%) than in the clay loam (9%) (Figure 2.11). However, PUE at the 15 mg kg-1 rate was not affected by soil. By comparison, in the third phase, the PUE at the 7.5 mg kg-1 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.

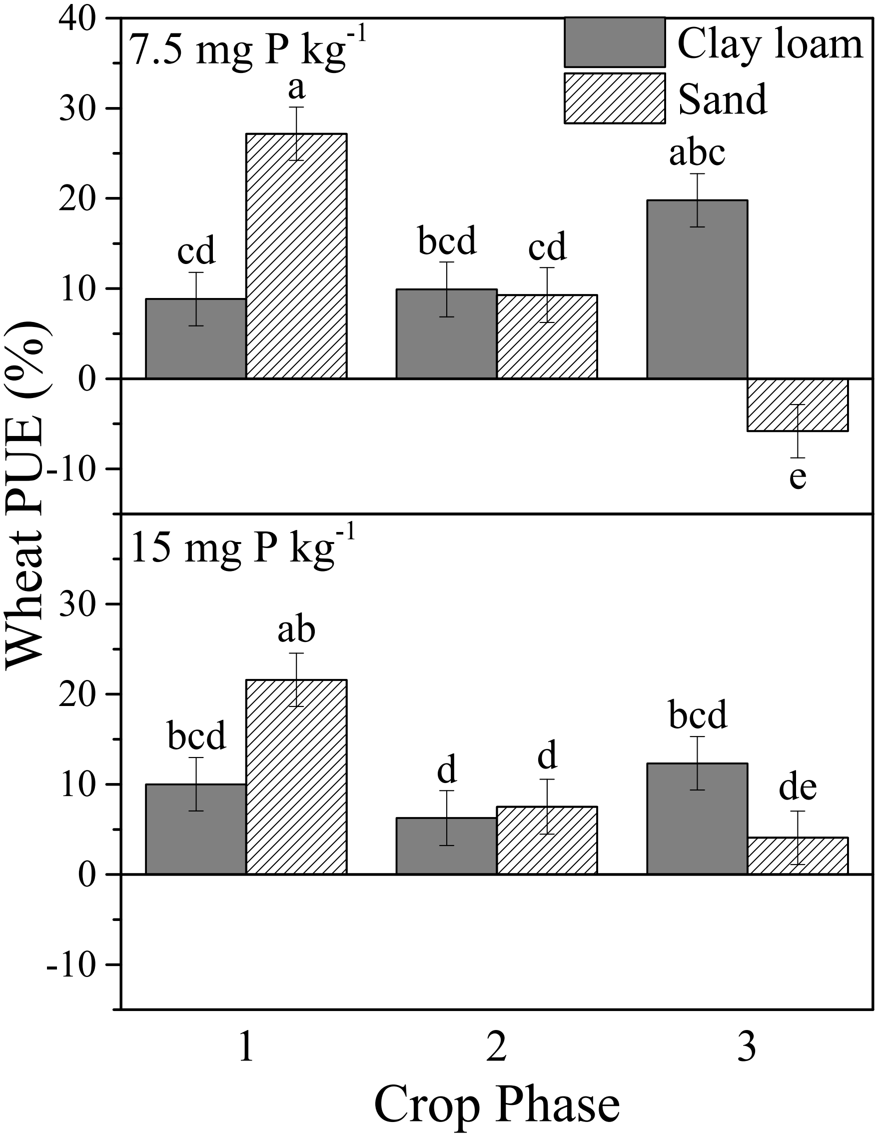

Figure 2.11 Wheat P uptake efficiency (PUE) as affected by soil, P rate, and crop phase. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure (P > 0.05). Error bars represent standard errors of the least squares means.

2.4.6 Agronomic Phosphorus Use Efficiency

2.4.6.1 Canola. Phosphorus source effects on AE of canola were significant but varied with phase, as indicated by the significant P-source × phase interaction (P = 0.003) (Table 2.3). 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. No significant differences were detected between struvite and MAP or CMAP in all three phases (Figure 2.12).

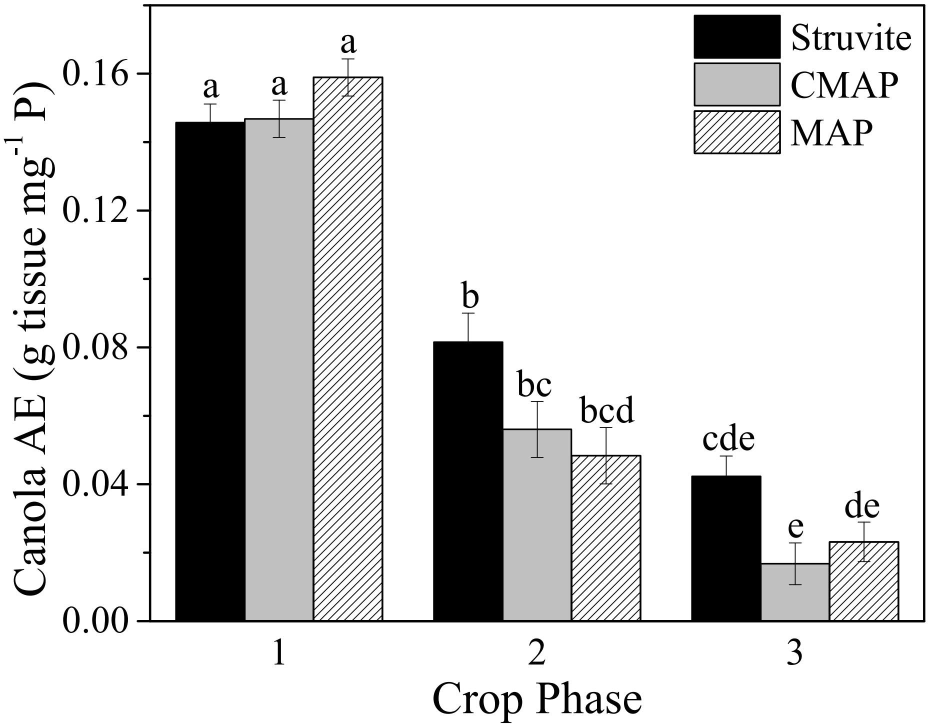

Figure 2.12 Phosphorus source and crop phase effects on agronomic P use efficiency (AE) of canola. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure (P > 0.05). Error bars represent standard errors of the least squares means.

There was a significant placement × crop phase interaction (P = 0.001) for AE (Table 2.3). Seedrow placement produced significantly greater AE than sidebanding in the first phase (Figure 2.13). 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.

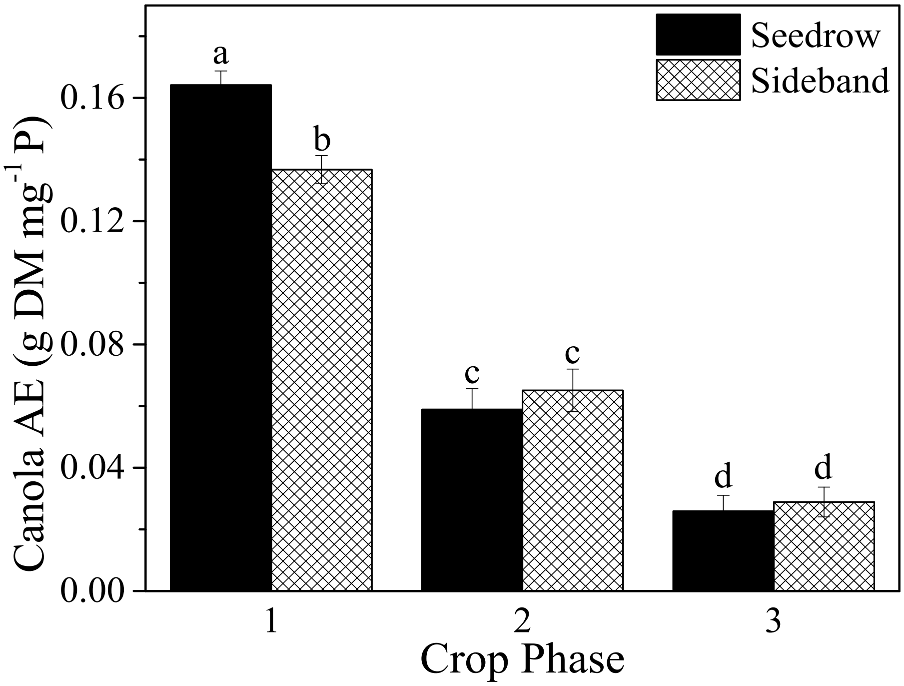

Figure 2.13 Phosphorus placement and crop phase effects on agronomic P use efficiency (AE) of canola. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

There was also a significant rate × soil × crop phase interaction (P = 0.03) (Table 2.3). 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 the 15 mg P kg^{-1} rate in the first phase, with no significant differences between the rates in subsequent phases (Figure 2.14).

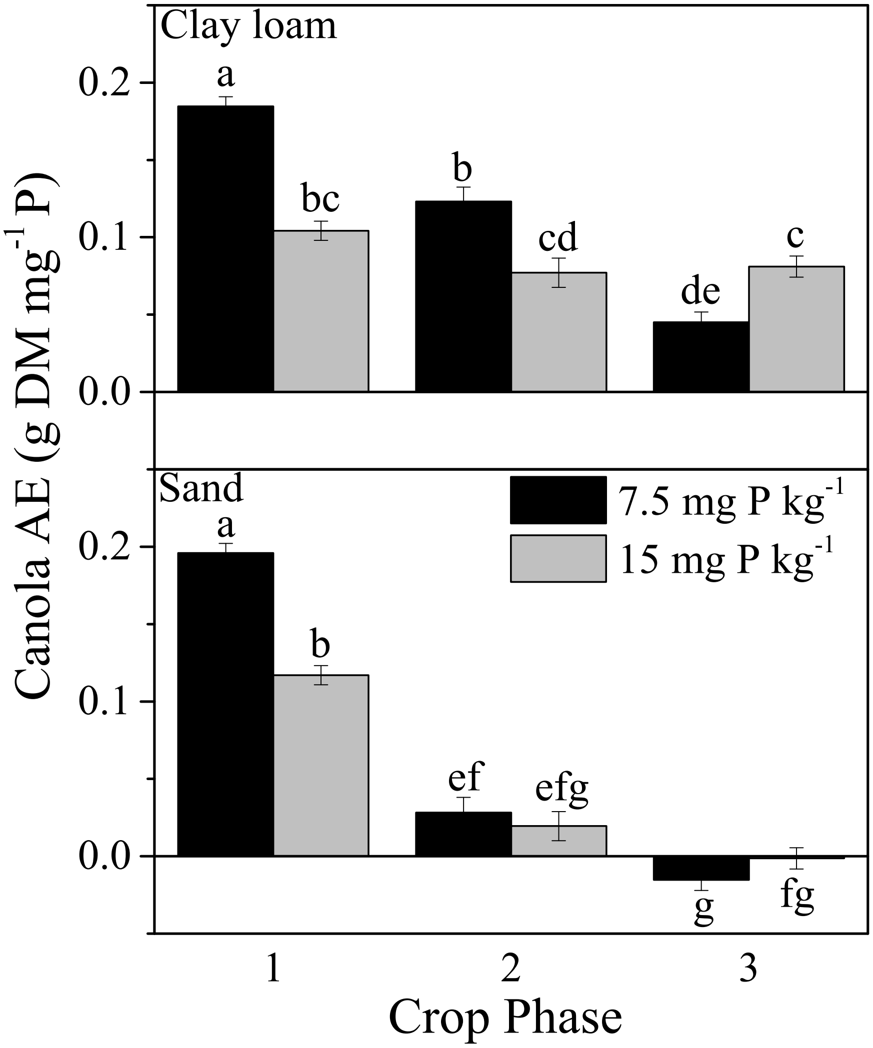

Figure 2.14 Effects of P rate, soil, and crop phase on agronomic P use efficiency (AE) of canola. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure (P > 0.05). Error bars represent standard errors of the least squares means.

2.4.6.2 Wheat. There was a significant rate × phase effect on AE of wheat ($P = 0.049$) (Table 2.3), but, due to the relatively conservative nature of the Tukey-Kramer procedure, mean comparisons did not show any differences between the rates in all phases. However, there was a tendency for greater AE with the 15 mg P kg^{-1} rate than with the 7.5 mg P kg^{-1} rate in the first phase, with smaller differences between the rates in subsequent phases, which both produced significantly lower AE values (0.004 – 0.03 g DM mg^{-1} P) than the first phase. For both rates, AE was significantly greater in the first crop phase than in the second phase, with no further decline in the third phase. However, for the 15 mg P kg^{-1} rate, there was no significant difference between AE in the first phase (0.047 g DM mg^{-1} P) and that in the third phase (0.031 g DM mg^{-1} P) (Figure 2.15).

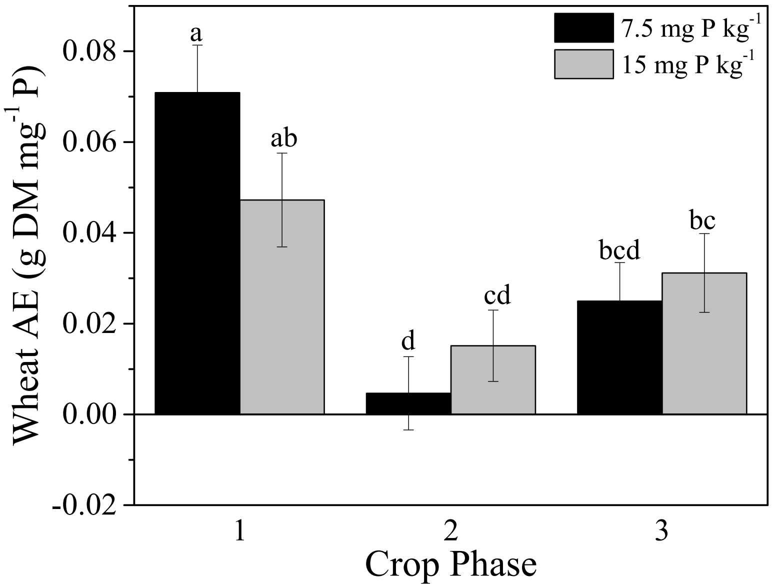

Figure 2.15 Phosphorus rate effects on agronomic P use efficiency (AE) of wheat over 3 growth phases. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

There was also a significant soil × phase interaction ($P = 0.002$), although mean comparisons did not indicate any significant differences between the soils in all phases (Figure 2.16). 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.

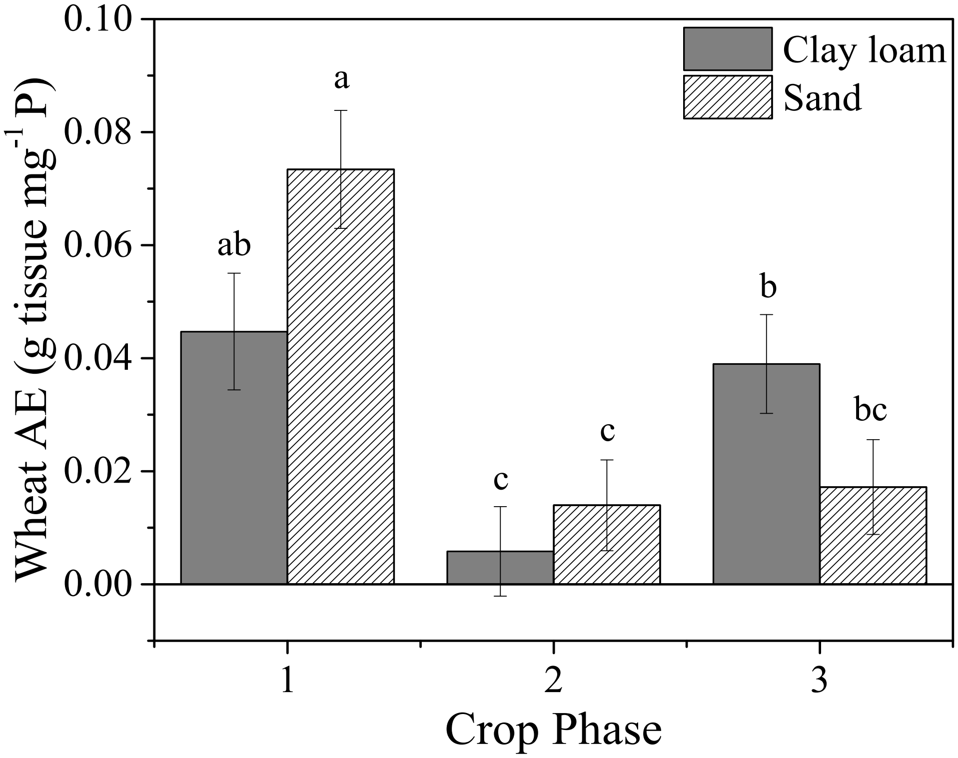

Figure 2.16 Wheat agronomic P use efficiency (AE) as influenced by soil type and crop phase. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

2.4.7 Crop Sequence Effects on Cumulative Phosphorus Uptake and Uptake Efficiency

There was a significant rate effect on cumulative P uptake, averaged over crop sequences ($P < 0.001$) (Table 2.4). 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 sequence, but the differences varied with soil ($P < 0.001$ for the crop sequence × 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 2.17).

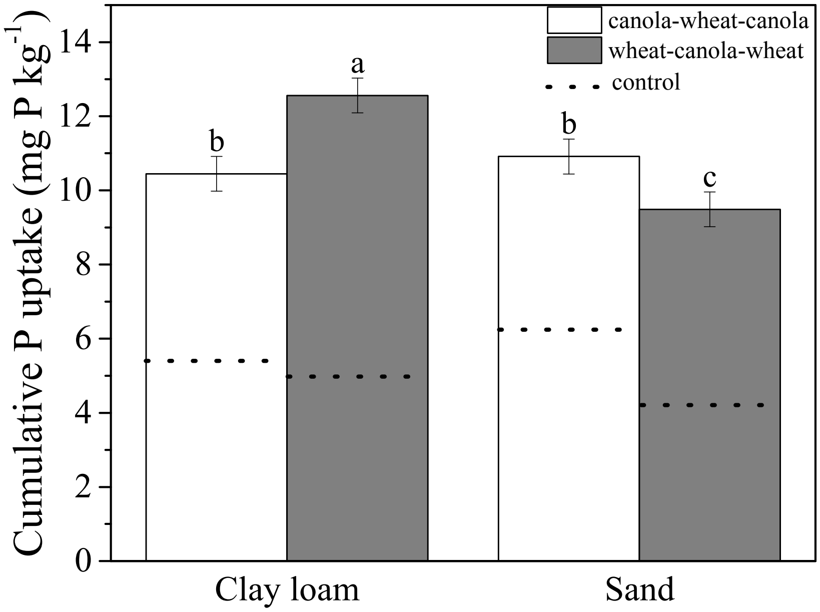

Figure 2.17 Effects of soil texture on the cumulative P uptake of three crop phases of canola-wheat-canola (CWC) or wheat-canola-wheat (WCW). Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

Table 2.4 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	10.7	54.5
wheat-canola-wheat	11.0	37.9
P-source (P)		
CMAP	10.9	46.9
MAP	10.9	47.1
Struvite	10.8	44.6
Rate (R, mg P kg^{-1})		
7.5	9.6	49.8
15	12.1	42.6
Application method (Ap)		
Seedrow	10.9	45.9
Sideband	10.8	46.5
Soil (S)		
Clay loam	11.5	51.1
Sand	10.2	41.3
	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 × S	0.06	0.02
Cs × S	< 0.001	0.22

† Two-, 3-, 4-, and 5-way interactions had P > 0.1 for both parameters are not presented.

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 2.4). Struvite produced greater PUE in the clay loam (54%) than in the sand (35%), but there were no significant soil effects for MAP and CMAP (Figure 2.18).

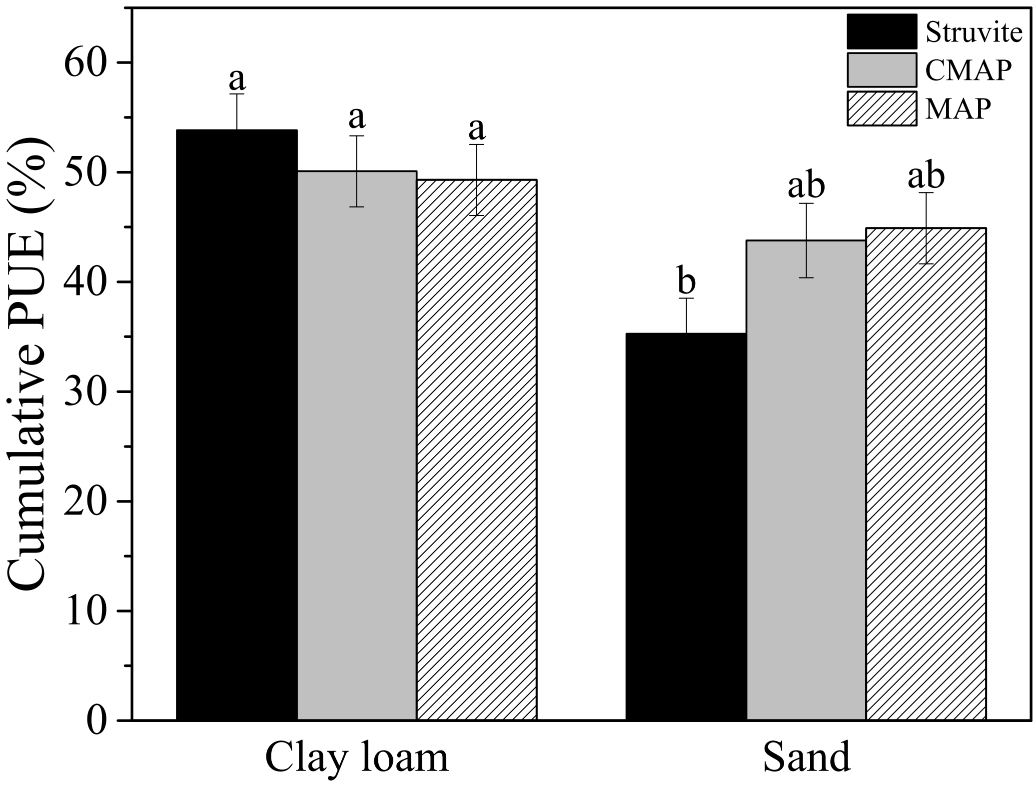

Figure 2.18 Cumulative P uptake efficiency (PUE) for 3 phases of canola and wheat crop sequences as affected by P-source and soil. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of the least squares means.

2.4.8 Bicarbonate-Extractable Phosphorus Concentration

2.4.8.1 Canola. In the clay loam, residual Olsen P concentration after harvesting the first canola crop was significantly greater than the control (4.7 mg kg^{-1}) only when the 15 mg P kg^{-1} of MAP was applied (7.3 mg kg^{-1}), regardless of placement method, and when the 15 mg P kg^{-1} of struvite was sidebanded (7.1 mg kg^{-1}). Residual Olsen P concentrations in all other treatments were not significantly different from the control (Table AII.3). In the sand, only the 15 mg P kg^{-1} rate of MAP gave significantly greater residual Olsen 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 relative to the control of canola after the third phase.

Phosphorus source effects on residual Olsen P concentration after canola harvest varied with placement method and soil type, as indicated by the significant P-source × placement × soil interaction (P = 0.03) (Table 2.5). In the clay loam, seedrow-placed MAP produced significantly greater residual Olsen P concentration than CMAP but both did not significantly differ from struvite. Conversely, there were no significant differences among the sources when P was sidebanded. In the sand, residual Olsen P after MAP application was significantly greater than that after struvite, but both were not significantly different from CMAP. For all P-sources, there were no significant differences between the placement methods, regardless of soil type. Also, residual Olsen P concentration was significantly greater in the clay loam than in the sand for all P-sources regardless of placement (Figure 2.20).

Table 2.5 Residual Olsen P concentration after canola and wheat harvests as affected by crop phase, P-source, rate, application method, and soil type.

†Effect	Residual Olsen P Canola	 Wheat
Crop phase (C)	mg P kg^{-1} soil	
1	4.7	5.5
2	3.9	3.1
3	3.3	2.8
P-source (P)		
CMAP	3.8	3.6
MAP	4.2	4.0
Struvite	3.8	3.9
Rate (R)		
7.5 mg P kg^{-1}	3.6	3.3
15 mg P kg^{-1}	4.3	4.3
Placement (Ap)		
Seedrow	3.9	3.8
Sideband	4.0	3.8
Soil (S)		
Clay loam	4.9	4.7
Sand	3.1	2.9
	P-value	
C	<0.001	<0.001
P	<0.001	0.004
R	<0.001	<0.001
Ap	0.54	0.86
S	<0.001	<0.001
P × C	0.04	0.02
P × R	0.001	0.43
P × S	0.003	0.0003
R × S	0.06	0.15
R × C	<0.001	<0.001
S × C	<0.001	<0.001
P × Ap × S	0.03	0.04
P × Ap × C	0.94	0.049
P × R × Ap × S	0.57	0.04

† Two-, 3-, 4-, and 5-way interactions with P values > 0.1 are not presented.

Analysis of variance of the factorial component (excluding the controls) showed a significant P-source × crop phase interaction (P = 0.04) on residual Olsen P (Table 2.5). In the first phase, residual Olsen P after MAP application was significantly greater (5.1 mg kg^{-1}) than that after struvite (4.5 mg kg^{-1}) or CMAP (4.5 mg kg^{-1}), which were not significantly different (Figure 2.19). No significant differences were observed among the sources in the second and third phases. For all P-sources, residual Olsen P declined with subsequent canola harvests.

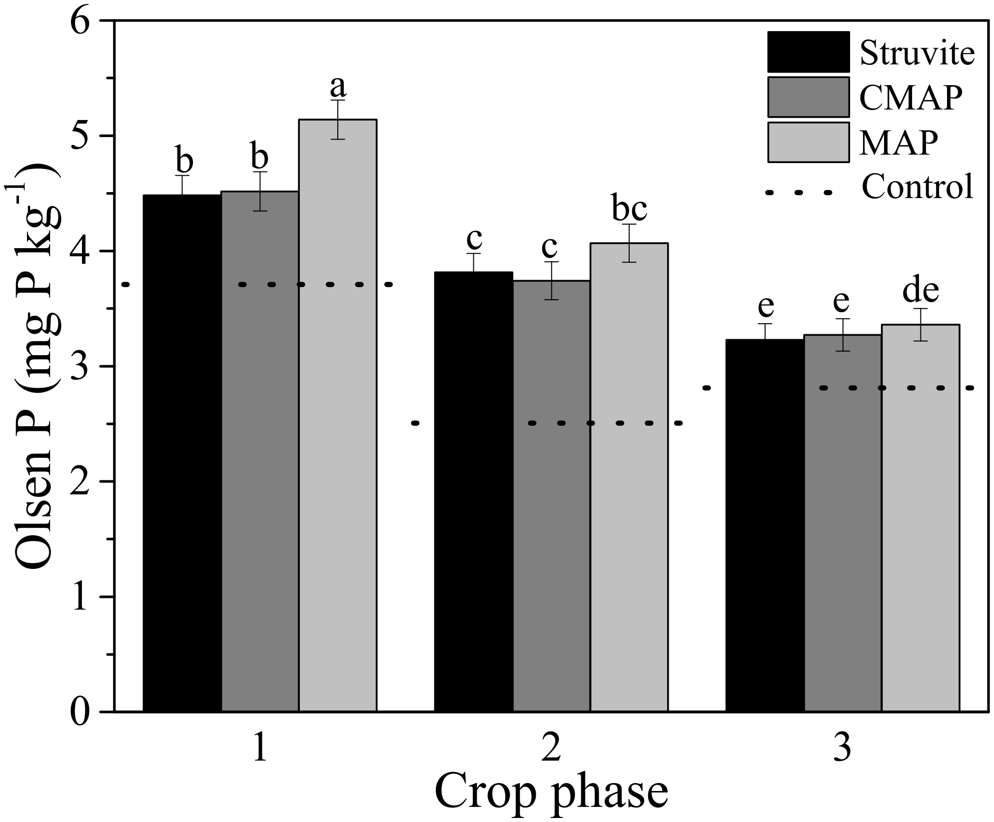

Figure 2.19 Residual Olsen P concentration after harvesting canola, as affected by P-source and crop phase. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure (P > 0.05). Error bars represent standard errors of least squares means.

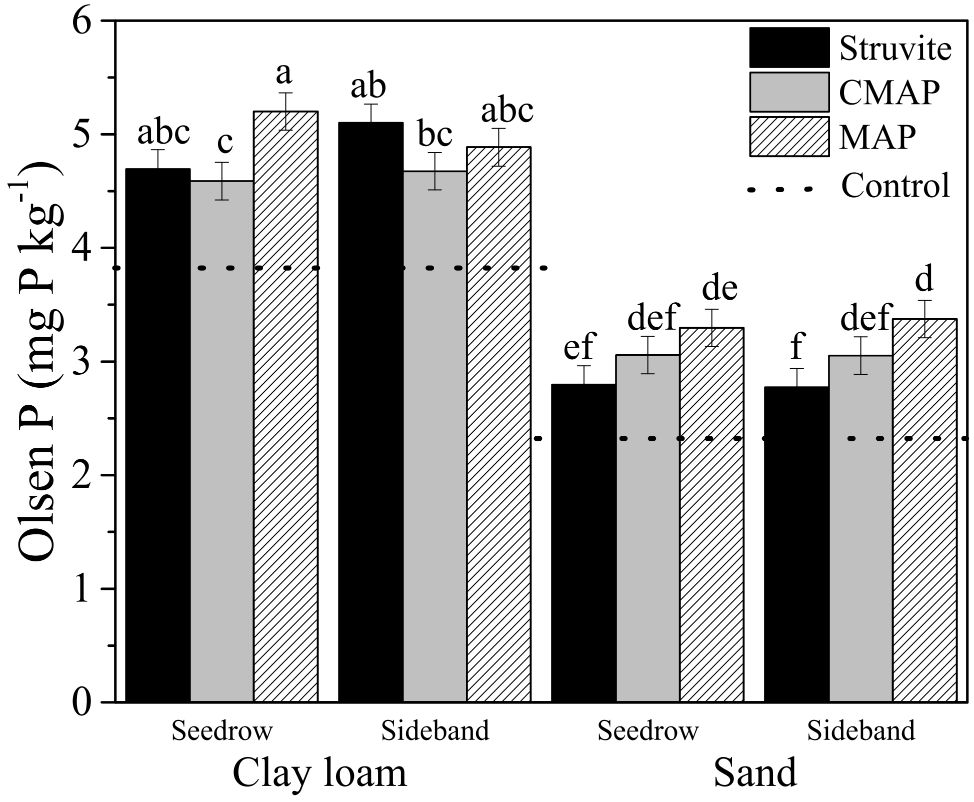

Figure 2.20 Residual Olsen P concentration after harvesting canola, as affected by P-source, placement method, and soil. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure (P > 0.05). Error bars represent standard errors of least squares means.

There was a significant soil × crop phase interaction (P <0.001) (Table 2.5) on residual Olsen P after harvesting canola. In all phases, residual Olsen P was significantly greater in the clay loam than in the sand (Figure 2.21). Olsen P in the clay loam declined with each subsequent harvest, but, in the sand, there was no significant decrease after the second harvest.

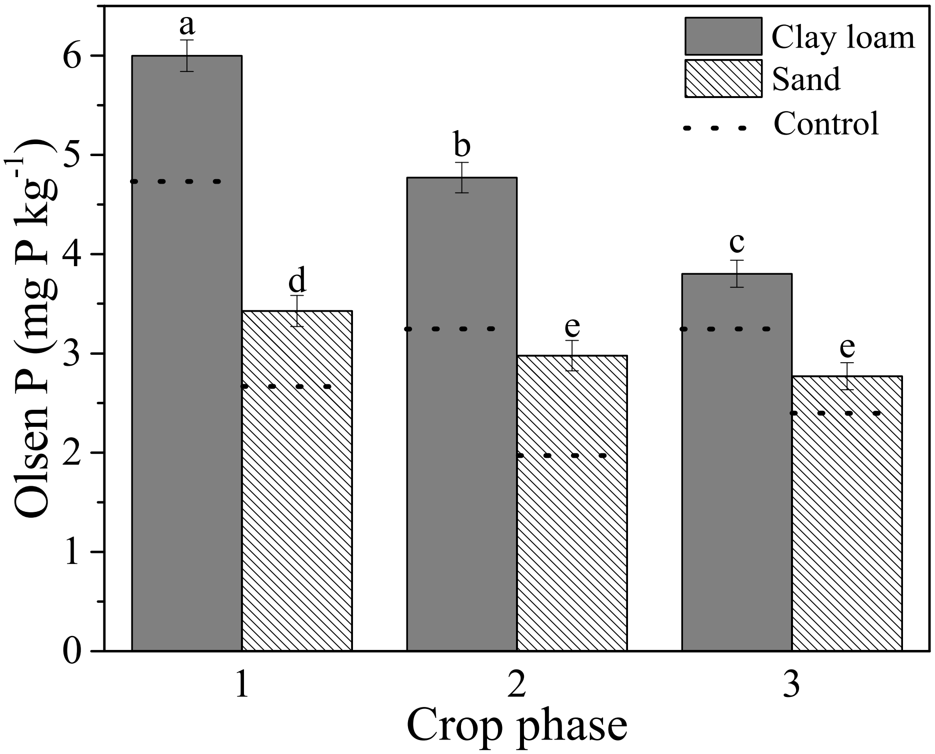

Figure 2.21 Residual Olsen P concentration after harvesting canola, as affected by soil and crop phase. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of least squares means.

Rate effects on residual Olsen P were significant but varied with crop phase due to the significant rate × crop phase interaction ($P < 0.001$) (Table 2.5). After the first and second canola harvests, residual Olsen P was significantly greater when P was applied at the 15 mg P kg^{-1} rate than at the 7.5 mg P kg^{-1} rate, regardless of soil type, application method, or P-source (Figure 2.22). Conversely, no significant differences were observed between the rates in the third phase. For both rates, residual Olsen P declined significantly with each subsequent canola harvest.

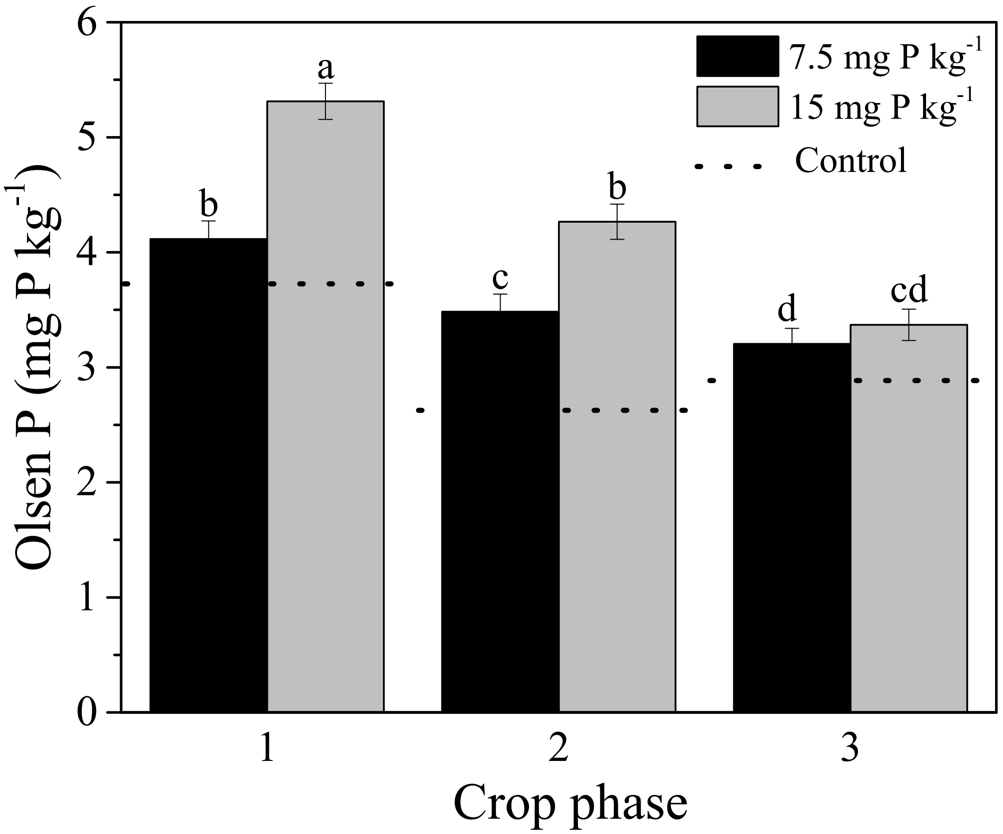

Figure 2.22 Residual Olsen P concentration after harvesting canola, as affected by soil P rate and crop phase. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of least squares means.

2.4.8.2 Wheat. The results of the factorial plus control component of the ANOVA (Table AII.3) showed that after the first wheat harvest, only the 15 mg P kg^{-1} rate of struvite produced significantly greater residual P concentration (9.5 mg kg^{-1}) than the control (4.8 mg kg^{-1}) in the clay loam. However, no significant differences were observed between P-fertilized soils and the controls in the second (3.0 mg kg^{-1}) and third (2.4 mg kg^{-1}) phases. In the sand, only the 15 mg P kg^{-1} rate of MAP (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, regardless of placement, compared to the control in the first phase (1.9 mg kg^{-1}). 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 of wheat.

Analysis of variance of the treatments excluding the controls showed a significant rate × crop phase interaction for residual Olsen P ($P < 0.001$) (Table 2.5). Residual Olsen P concentration from the 15 mg kg^{-1} rate was significantly greater than that from the 7.5 mg kg^{-1} rate in all phases (Figure 2.23). For both rates, residual Olsen P concentration significantly declined with each subsequent wheat harvest, regardless of P-source, placement or soil.

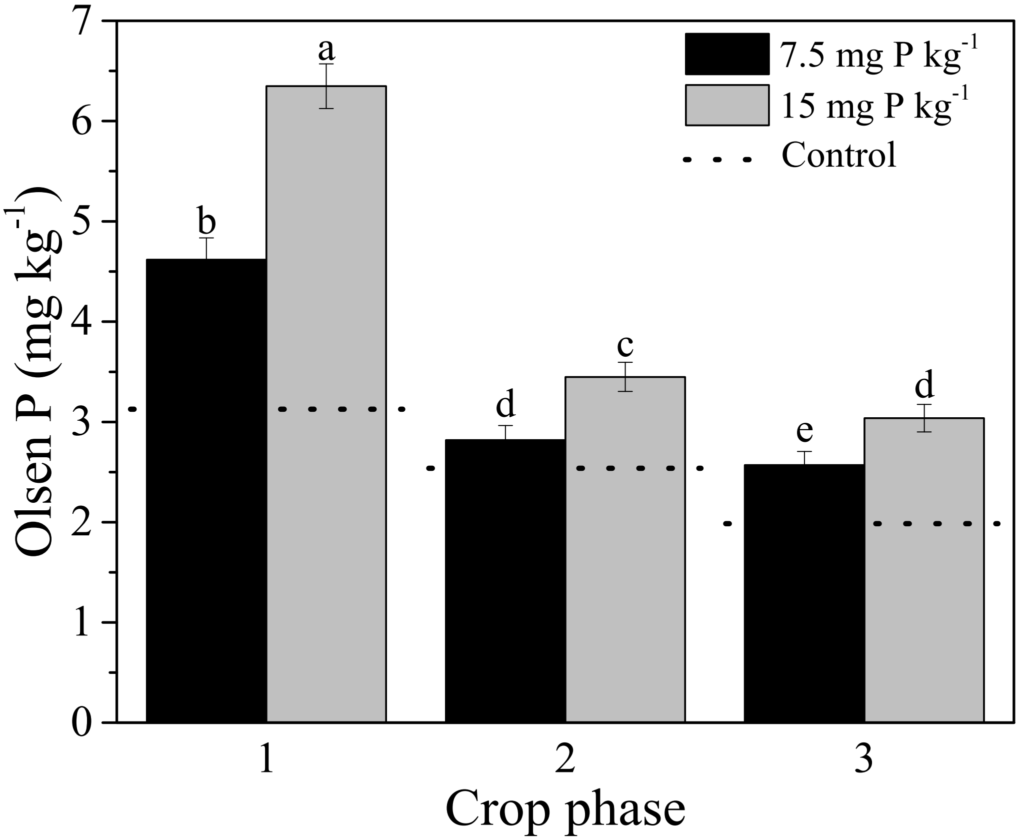

Figure 2.23 Residual Olsen P concentration after harvesting wheat as affected by P rate and crop phase. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of least squares means.

Phosphorus source effects were significant for residual Olsen P, but varied with application method and crop phase as shown by the significant P-source × placement × crop phase interaction ($P = 0.049$) (Table 2.5). For all P-sources, there were significant decreases in residual Olsen P concentration in the second phase regardless of placement. There was no further decrease in the third phase when all P-sources were placed in the seedrow and when MAP and CMAP were sidebanded. However, when struvite was sidebanded, residual Olsen P concentration significantly declined in both the second and third phases. Overall, there were no significant differences among the P-sources in all phases, regardless of placement method (Figure 2.24).

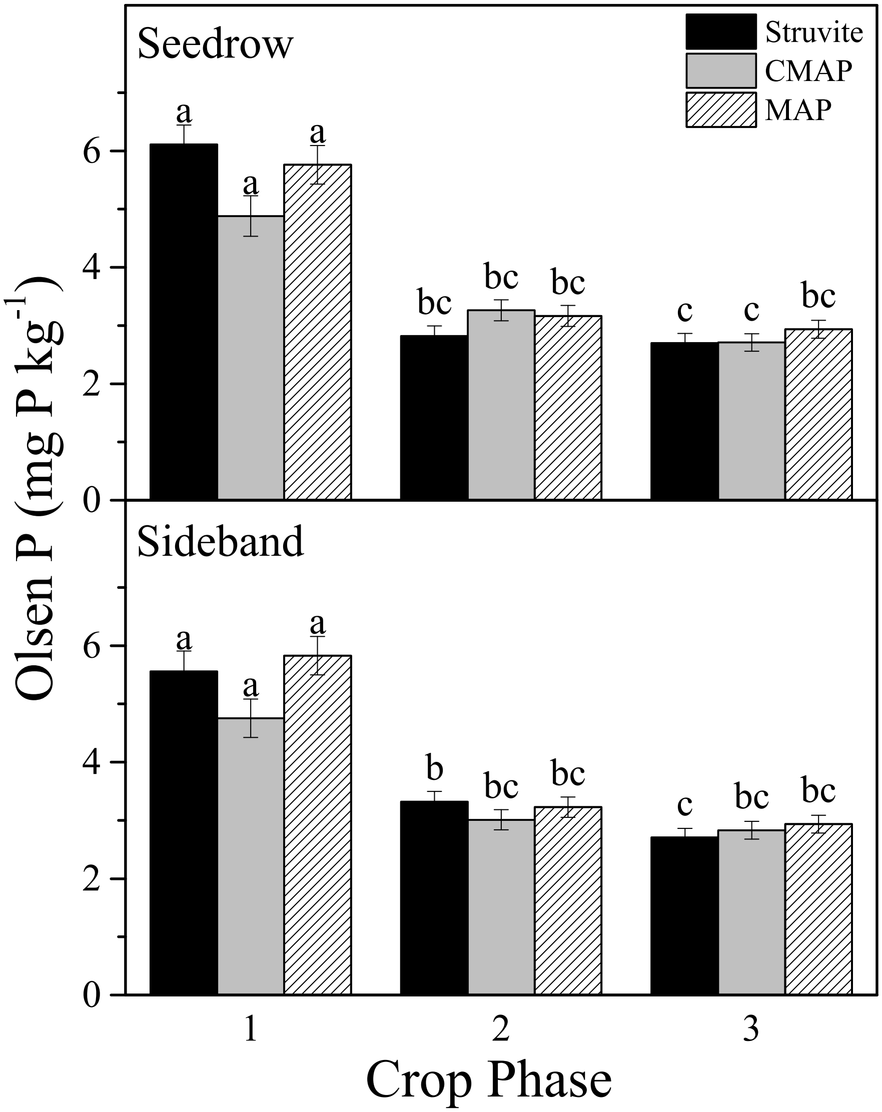

Figure 2.24. Residual Olsen P concentration after harvesting wheat as affected by P-source, application method, and crop phase. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure (P > 0.05). Error bars represent standard errors of least squares means.

There was a significant soil × crop phase interaction (P <0.001) for residual Olsen P concentration (Table 2.5). In all crop phases, residual Olsen P concentration was significantly greater in the clay loam than in the sand (Figure 2.25). In the clay loam, residual Olsen P concentration decreased with each subsequent harvest, while in the sand, there was no significant difference between the second and third phases.

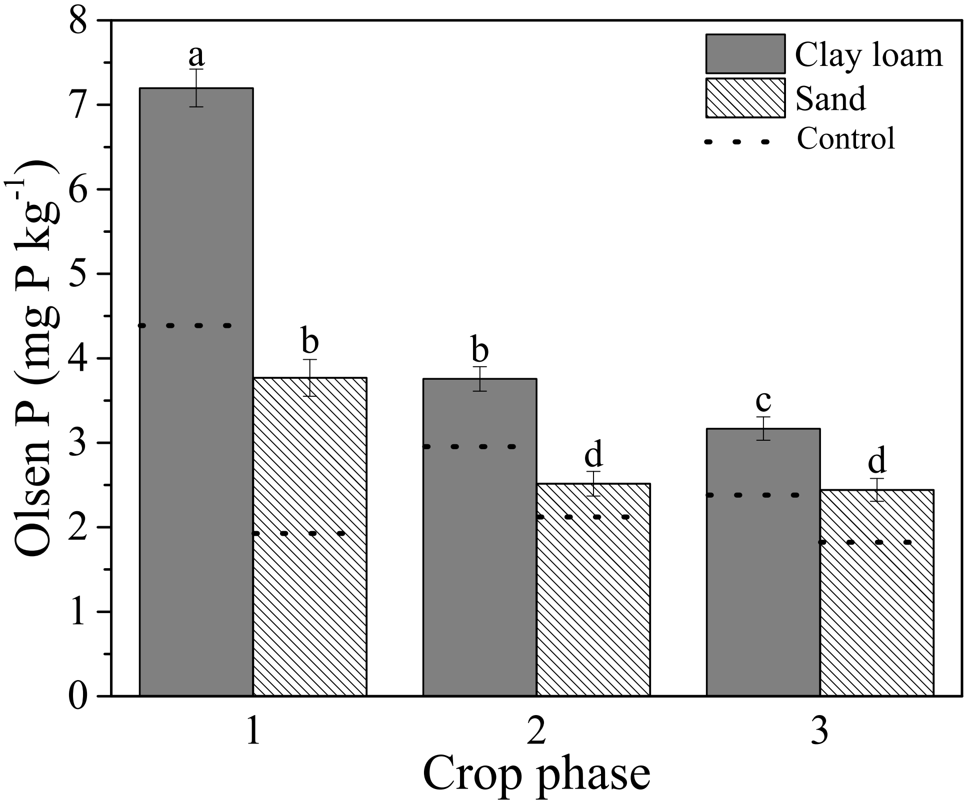

Figure 2.25 Residual Olsen P concentration after harvesting wheat as affected by soil and crop phase. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure (P > 0.05). Error bars represent standard errors of least squares means.

There was a significant P-source × rate × placement × soil interaction (P = 0.04) (Table 2.5). At the 15 mg kg $^{-1}$ rate, struvite was significantly greater than CMAP when the P-sources were sidebanded in the clay loam. However, when struvite was sidebanded in the clay loam or seedrow placed in the sand residual Olsen P at the 15 mg kg $^{-1}$ rate was significantly greater than that at the 7.5 mg kg $^{-1}$ rate. Overall, all P-sources did not differ significantly between the rates, regardless of soil or placement method (Figure 2.26).

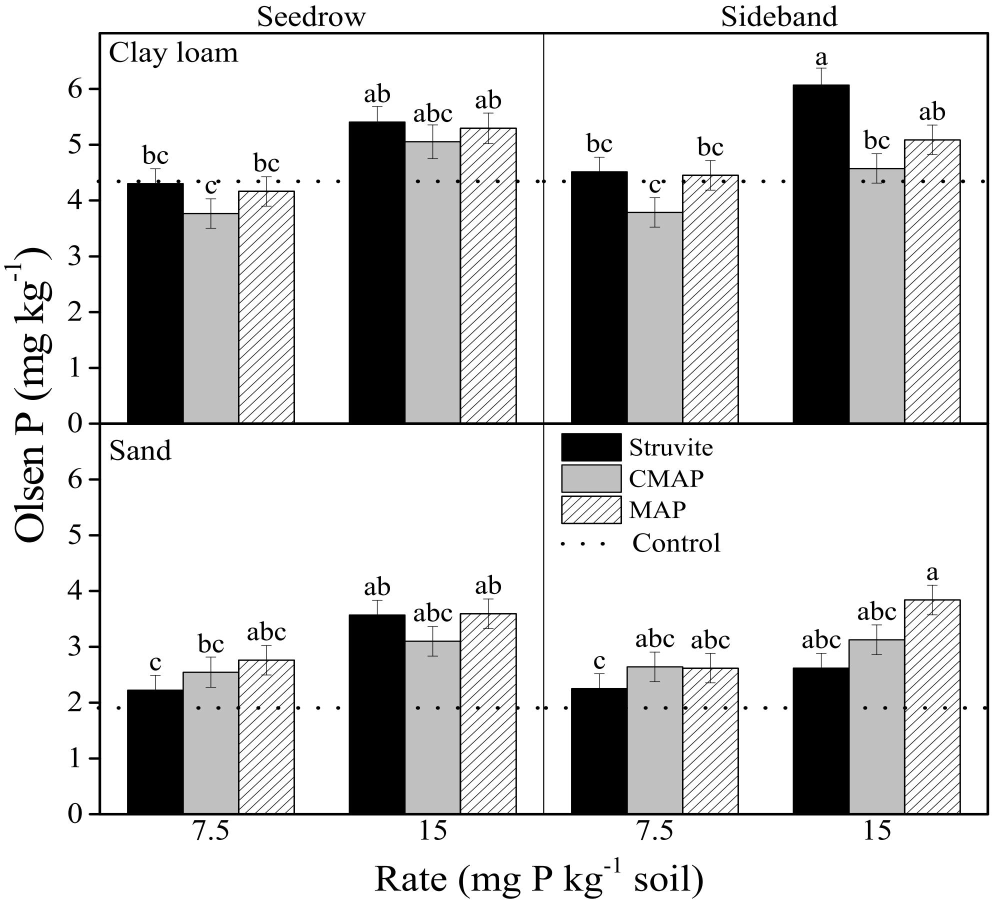

Figure 2.26 Residual Olsen P concentration after harvesting wheat as affected by P-source, rate, application method, and soil. Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$). Error bars represent standard errors of least squares means.

2.5 Discussion

Overall, the recovered struvite used in this study showed an agronomic performance that equaled or exceeded that of MAP and CMAP for both canola and wheat production. For example, DMY, P uptake and PUE observed for canola in the first phase did not differ significantly among P-sources. The same relative competitiveness of struvite was observed in both soils for wheat DMY, PUE, and AE in all phases, although wheat did not give significant responses to P application. These results were despite the slow-release properties of the recovered-struvite product, which comprised of P forms ($MgNH_4PO_4 \cdot 6H_2O$-P, Ca-P, and organic-P) of low solubilities. Phosphorus availability from the recovered struvite was largely determined by the $MgNH_4PO_4 \cdot 6H_2O$, which accounted for >80% of the P in the product (Jordaan et al., 2010). In pure water, the solubility of $MgNH_4PO_4 \cdot 6H_2O$ at 25°C is in the range 160–200 mg L^{-1} (Barak and Stafford, 2006). This solubility decreases with increasing pH and decreasing temperature (Bhuiyan et al., 2007). 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 slow (Barak and Stafford, 2006). The P (20%) in calcium phosphates and organic P forms was also potentially slowly available due to low solubility and high dependence on mineralization rates, respectively (Sharpley et al., 2003). However, the recovered-struvite product showed agronomic effectiveness not significantly different from the commercial sources.

On the other hand, wheat P uptake from struvite was significantly lower than that from MAP and CMAP in the first phase, although the DMY was not significantly reduced. 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 relative to wheat may have offset the low P release from struvite, leading to similar P uptake from the struvite and the commercial sources by canola in the first phase. The effectiveness of struvite may also have been optimized with canola due to enhanced solubility of the struvite product at low pH, such as in the rhizosphere of canola in P-deficient soils (Pearse et al., 2006). However, as reflected by the similar AEs for wheat from the P-sources, the differences between the amounts of P taken up by the wheat were not large enough to translate into significantly lower wheat DMY for struvite compared to the commercial P-sources.

The similar performance of struvite and the MAP fertilizers on DMY in the first crop phase 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 (0 – 10 mg P kg^{-1}) 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.

In the clay loam, struvite produced greater canola DMY than MAP in the second phase and greater than both MAP and CMAP in the third phase. This indicates the ability of struvite to effectively supply P to canola for longer durations than MAP and CMAP in this soil. 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 from SRFs. 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).

Unlike canola, wheat showed no significant DMY and P uptake responses to P application in all phases. 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). The lack of response by wheat may be due to the relatively lower PUE of wheat compared to canola (Brennan and Bolland, 2001). Wheat requires higher rates of P than canola to produce significant yield responses. In addition, the consistently high wheat yields in the second and third crop phases may have been due to the increases in phosphatase activity and the abundance and diversity of P solubilizing soil microbes in the rhizosphere of the preceding canola crops (Solaiman et al., 2007), leading to enhanced P supply for subsequent wheat crops. Although we did not measure arbuscular mycorrhizal fungal infection in this study, arbuscular mycorrhizal symbiosis between wheat and soil fungi, which improves wheat P acquisition in P-deficient soils, has been suggested to explain the poor P application response of wheat. A study by Shukla et al. (2012) showed that mycorrhizal infection of wheat and other crops was more important than P application as it explained up to 78% of the variation in plant growth.

For all P-sources, 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., 2007; 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 sidebanding (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 sidebanding (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 sidebanding (97%), overall, DMY in this study did not appear to have been adversely affected by toxicity due to seedrow placement (Figure 2.4). In fact, canola DMY and AE in the first phase were significantly greater for seedrow placement than for sidebanding. This is because seed-placement improves accessibility of P during early seedling development (Grant and Bailey, 1993) and canola biomass can compensate for low plant stands. 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 (Table 2.2), there may be greater short-term availability of P in the sand due to relatively lower P retention capacity compared with the clay loam (Ige et al., 2005). The CEC, clay content, OC 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, the 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 and the differences in P release patterns of the P-sources, 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 less fertilizer P was required for canola DMY and P uptake responses compared to 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).

2.6 Conclusions

Overall, results from this study indicate that struvite was not significantly different to the commercial fertilizers, MAP and CMAP, in supplying P and supporting good canola and spring wheat DMY. Thus, struvite may be a viable alternative to the widely used MAP in canola-wheat rotations. 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).

Struvite is also a potentially better alternative to high-technology controlled-release fertilizers such as CMAP and its adoption within agricultural systems is 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). 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.

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3. EFFECTS OF SEED-PLACED HOG MANURE-RECOVERED STRUVITE ON CANOLA SEEDLING EMERGENCE

3.1 Abstract

Seedling toxicity is a major limitation to phosphorus (P) fertilizer rates that can be applied in the seedrow of sensitive crops such as canola. In this growth room bioassay, we tested whether a high rate of struvite recovered from liquid hog manure could improve seedling emergence in canola relative to monoammonium phosphate (MAP) and polymer-coated MAP (CMAP). Twenty canola seeds per pot were planted in two low-P soils (a Gleyed Regosolic sand (Entisol) and an Orthic Black Chernozemic clay loam (Udic Boroll)). The P-sources were applied in the seedrow at rates of 7.5 or 15 mg P kg^{-1} soil, either in 15 mm or 25 mm bands, which correspond to 5.5% and 10.9% seedbed utilization (SBU), respectively. The higher rate of MAP reduced overall seedling emergence in the clay loam by >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 was likely 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. Therefore, struvite can be used as a P-source for canola at higher rates than those recommended for MAP, with a much lower risk of seedling damage, thereby cutting yield losses and costs associated with replanting.

3.2 Introduction

Canola is one of the most important crops in the Canadian economy (Canola Council of Canada, 2014; Casséus, 2009) and strategies to improve and maintain high yields and quality are continually being sought (Grant and Bailey, 1993). One of the major challenges in canola production is the management of P fertilizers (right source, application rate, time, and placement), specifically the efficient supply of adequate P to meet the demand for high yields, without damaging the crop or threatening the environment. Successful and timely seedling establishment is essential for achieving optimal canola yield potential. Canola yield potential is highly dependent on the complex process of seedling emergence, which involves seed germination and early seedling development. Seedling emergence is greatly influenced by the rate at which dormancy breaks and the rate of repair and synthesis of seed structures, leading to the growth of the embryo and subsurface seedling elongation (Bewley, 1997; Nonogaki et al., 2010). Therefore, optimizing seedbed conditions for successful and timely seedling emergence is very important for attaining optimal yields. When seedbed conditions are suboptimal, seedling emergence is usually compromised, the extent of which varies with crop species and the extremity of the limiting conditions.

Canola seeds are typically sensitive to extreme environmental conditions such as extremes of temperature, moisture, and salt concentrations (Bradford, 1990; Pace and Benincasa, 2010). Due to the absence or inadequate development of stress-tolerance mechanisms in young plants (Bartels and Sunkar, 2005), exposures of germinating seeds and developing seedlings to stressful conditions can lead to acute toxicity damage. For instance, high moisture tension (dryness) or osmotic pressure (high solute concentrations) can lead to reduced intake of water (imbibition) during germination. Even viable seeds may fail to germinate or complete emergence when exposed to conditions of low soil water potential, such as those in fertilizer bands (Bradford, 1990). Therefore, fertilizer management should not only prioritize the adequate supply of nutrients, but also the optimization of seedling emergence, as both are equally critical.

When fertilizers are applied to soils, especially in concentrated bands, they increase the salt concentrations in the vicinity of the zone of application as they dissolve. This is most apparent when highly soluble fertilizers such as MAP are applied. Damage from seed-placed MAP is more pronounced if the soil temperature or moisture content is low, and seeds are exposed to the salts for longer periods, which aggravates injury (Lindstrom et al., 1976). On the Prairies, canola seeding is done in early spring, which is characterized by low soil temperatures, making seed-placement of fertilizers highly risky.

With the limited mobility of P in soils, and also its high susceptibility to fixation, the most efficient placement for canola is close to the seed, where the plants can access P early in the season (Grant and Bailey, 1993). However, seedrow-placement of high rates of MAP and other highly soluble P forms leads to high salt concentrations near the seeds, reducing seedling emergence (Henry et al., 1995). Given the high yield potential, hence high P requirements (40-50 kg P_2O_5 ha^{-1}) of current canola cultivars, recommended safe rates of seedrow-placed MAP in P deficient soils (22-28 kg P_2O_5 ha^{-1}) (Thomas, 2014) can supply only half the P requirements of the crop (Grant and Bailey, 1993). Alternatively, high rates of P can be sidebanded or broadcasted, but usually this is a trade-off with the high P use efficiency associated with seed-placement and also requires specialized seeding equipment. While fertilizer placement farther from the seed might address the problem of toxicity at high P rates, P uptake by the crop remains low due to the limited mobility of the nutrient in soil.

Fertilizer formulations and compositions also contribute to the variability in fertilizer toxicity, even when applied at the same rate. However, the width of the fertilizer/seed band or seedbed-utilization (SBU), soil physical and chemical properties, and the physical form and nutrient composition of a fertilizer are the critical factors influencing the safety of most fertilizers (Roberts and Harapiak, 1997). Lombi et al. (2004) reported that when placed close to seeds, liquid, powdery and fine textured fertilizers result in more damage than coarsely-granulated fertilizers, as they tend to dissolve faster and rapidly increase salt concentrations in the band. However, it has not been established if this also applies to SRFs such as CMAP or struvite. Although P is mostly applied as coarsely granulated MAP, the risk of seedling damage is still high enough as it sometimes translates to yield losses if compounded by other stresses such as inadequate moisture, diseases or pests.

The salt toxicity index for MAP (29.9%) is relatively low, making it safer than most ammonium-based fertilizers (Rader et al., 1943). 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). However, research has consistently shown that there is a risk of seedling toxicity associated with seed-placed MAP (Nyborg, 1961; Roberts and Harapiak, 1997). 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.

Many indices and measurements can be used to explain germination and emergence. However, as discussed by Ranal and Santana (2006), these indices have limitations and cannot adequately characterize seedling emergence in isolation because of the complexity of the process (Forcella et al., 2000). Many models can be used to comprehensively describe emergence (Brown and Mayer, 1988b), but the suitability of any one model depends on its ability to capture and preserve information about the start of emergence, the rate at which it proceeds and the final extent (Brown and Mayer, 1988a). In the present study, we fitted an exponential growth model to the emergence data to compare the relative seedling toxicity effects of seedrow-placed struvite, MAP, and coated-MAP (CMAP). There is a dearth of information on struvite performance on crops such as canola, and no studies have evaluated the effects of struvite on seedling emergence. Therefore, this study was conducted to characterize struvite with respect to canola seedling toxicity at different application rates and concentrations in the seedrow.

3.3 Materials and Methods

3.3.1 Hog manure recovered struvite and monoammonium phosphate fertilizers

Powdered struvite was precipitated from anaerobically digested hog manure effluent (Jordaan et al., 2010). Consistent with MAP granule sizes, the struvite was granulated by hand. Granular MAP and CMAP (11-52-0) were supplied by Agrium Inc. (Calgary, AB, Canada).

3.3.2 Soils

A dark-grey Gleyed Regosolic sand (Entisol), and an Orthic Black Chernozemic clay loam (Udic Boroll) were collected from the 0- to 15-cm depths and differed in texture. Soil analyses were conducted as previously described in Section 2.3.2.

3.3.3 Experiment setup

The bioassay was laid out in a CRD 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) 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 ~0.9 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 RO water was added to each pot to bring the moisture content to approximately 260 g kg^{-1} (65% 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.

3.3.4 Statistical Analyses

3.3.4.1 Analysis of Variance. Data was analyzed using the GLIMMIX procedure in SAS (SAS Institute, 2014). 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 in the model. The emerged seedlings in each of the two rows for each pot were treated as subsamples.

3.3.4.2 Nonlinear Modelling. 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. Also, the microenvironment of the soil surrounding each seed is very diverse. 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). Cumulative emergence data were fitted to six sigmoidal growth functions using the NLIN procedure in SAS (SAS Institute, 2014).

The most suitable function to describe canola emergence data was selected targeting practical relevance and simplicity (Brown and Mayer, 1988b; Torres and Frutos, 1990;

Vanclay and Skovsgaard, 1997). 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:

$$\text{Mitscherlich:} \quad E = M\left(1-\exp\left(-k\left(t-z\right)\right)\right) \qquad [5]$$

$$\text{Logistic:} \quad E = \frac{M}{\left(1+\exp\left(-kt+ß\right)\right)} \qquad [6]$$

$$\text{Gompertz:} \quad E = M\left(\exp\left(-\exp\left(-kt+b\right)\right)\right) \qquad [7]$$

where E is percentage emergence at time t (d), M is the asymptotic (final) emergence percentage, and k represents the mean relative cumulative emergence rate (d^{-1}), and is obtained from an integration of the relative cumulative emergence rate between E = 0 and E = M (Torres and Frutos, 1990). Parameter z represents the lag (time at point of inflection) while parameters ß and b do not have direct biological relevance but are inversely related to k to give the lag in the Logistic and Gompertz functions (Brown and Mayer, 1988b; Torres and Frutos, 1990). The lag values for the Gompertz function were derived after fitting the cumulative emergence data for each of the replicates, and are calculated as:

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

A repeated measures ANOVA of the lag values was done using PROC GLIMMIX in 2 steps (see section 3.3.4.1), consistent with the factorial plus control treatment structure.

The means were compared using the Tukey procedure. For final emergence (M) and mean relative cumulative emergence rate (k), differences among treatments were determined using the approximate 95% confidence intervals obtained from the model fitting. Treatments with overlapping confidence intervals were considered not significantly different (Motulsky and Christopoulos, 2003).

3.4 Results

3.4.1 Recovered Struvite and Soil Properties

The properties of the recovered struvite and soils used in the bioassay are presented in Sections 2.3.1 and 2.3.2. The recovered struvite was composed of 81% struvite-P, and 19% as calcium- or organic-P (Table 2.1). Both soils had Olsen P concentrations in the deficient range for canola and wheat (Table 2.2).

3.4.2 Final Seedling Counts at 16 Days after Planting

Final seedling counts in the controls did not differ significantly 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 54 % relative to the controls. In contrast, application at the 7.5 mg kg^{-1} rate (85%) did not significantly reduce the final counts in this soil. Similarly, struvite (90%) and CMAP (97%) did not significantly reduce final counts, regardless of P rate. Conversely, no treatments significantly reduced final counts relative to the control in the sand.

Table 3.1 Final seedling counts at 16 days after planting (DAP) as affected by P-source, P rate, seedbed-utilization (SBU), and soil type.

Effect	**Emerged seedlings (%)**
Soil (S)	
Clay loam	86
Sand	76
P-source (P)	
CMAP	86
MAP	69
Struvite	88
Rate (R)	
7.5	83
15	78
Seedbed utilization (SBU)	
10.9%	82
5.5%	80
	P-value†
S	< 0.001
P	< 0.001
R	0.025
SBU	0.3
S × P	< 0.001
S × R	0.2
P × R	< 0.001
S × SBU	0.43
P × SBU	0.13
R × SBU	0.76
S × P × R	0.01

† Three - and 4-way interactions with P values > 0.1 are not presented.

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 = 0.01) (Table 3.1) (Figure 3.1).

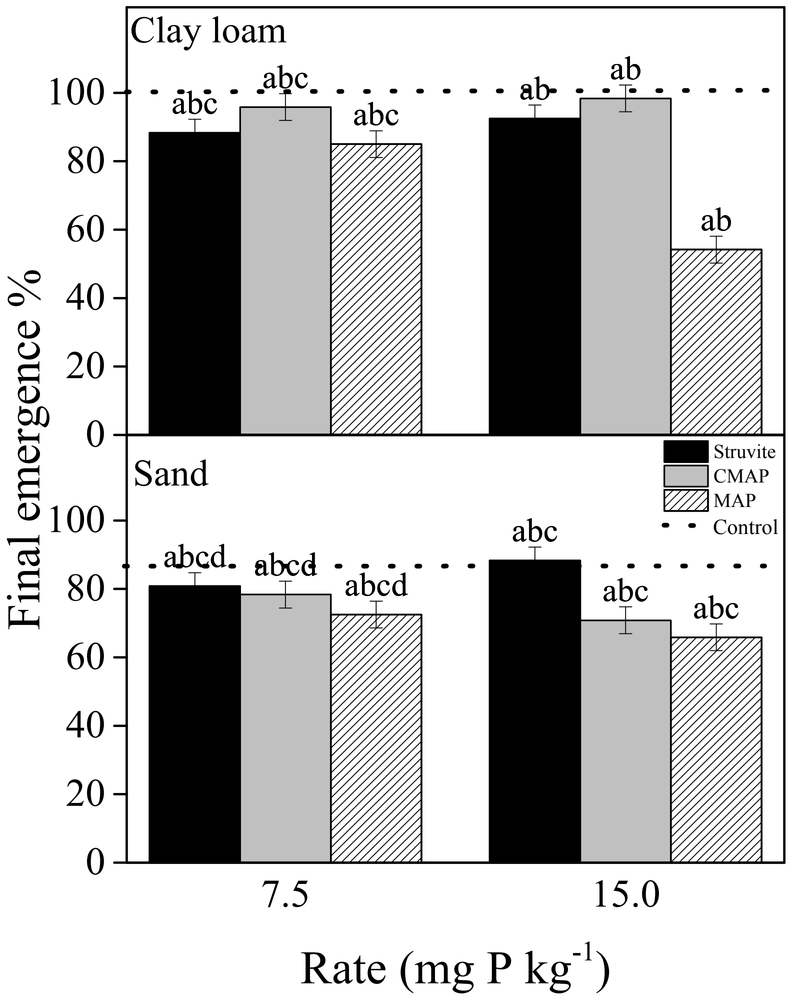


Figure 3.1 Effects of P-source, rate, and soil on final seedling counts (out of 10 planted seeds). Columns with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure (P > 0.05). Error bars represent standard errors of the least squares means.

3.4.3 Nonlinear Regression

The Mitscherlich function had the highest AIC value, while the Logistic and Gompertz functions had lower and very similar AIC values for most treatments (Table 3.2). However, the Gompertz function had consistently lower values than the Logistic function for all treatments; therefore the Gompertz function was chosen to describe the data.

Table 3.2 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

3.4.3.1 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 3.3). All MAP treatments significantly reduced final emergence percentage. Relative to the control (100%), the largest reduction in final emergence percentage was by 52% when the fertilizer was applied at the 15 mg P kg^{-1} at the 5.5 % SBU (emergence = 48.3%). The sidebanded 7.5 mg kg^{-1} rate resulted in the smallest reduction (12%) for MAP (Figure 3.2). Except for the narrow-banded (low SBU) 7.5 mg kg^{-1} rate (final count = 81%), all struvite treatments significantly reduced final seedling counts 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 3.3). 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 3.3 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 a	2.6	100 a	3.5 a	8.7 a	2.7 a
MAP-narrow-7.5	82 ab	14.3	80 d	1.7 ab	4.8 a	2.9 a
MAP-wide-7.5	88 ab	9.1	88 c	1.9 ab	5.5 a	2.8 a
MAP-narrow-15	48 c	13.9	48 f	1.9 ab	5.5 a	3.1 a
MAP-wide-15	60 bc	18. 7	58 e	1.7 ab	5.2 a	3.0 a
CMAP-narrow-7.5	97 a	5.4	96 b	3.1 ab	7.8 a	2.6 a
CMAP-wide-7.5	95 a	4. 9	95 b	3.3 ab	8.3 a	2.8 a
CMAP-narrow-15	100 a	4.5	99 a	2.1 ab	5.5 a	2.6 a
CMAP-wide-15	97 a	5.7	96 b	2.0 ab	5.3 a	2.7 a
Struvite-narrow-7.5	82 ab	14. 8	81 d	1.5 b	4.0 a	2.8 a
Struvite-wide-7.5	95 a	10.2	93 b	1.9 ab	4.9 a	2.6 a
Struvite-narrow-15	93 a	15.1	92 bc	1.8 ab	4.8 a	2.7 a
Struvite-wide-15	92 a	15.8	91 bc	2.0 ab	5.3 a	2.7 a
Sand						
Control	87 a	14.7	86 a	0.5 b	2.9 bc	6.0 ab
MAP-narrow-7.5	80 a	9.8	66 b	0.4 b	2.6 bc	6.3 a
MAP-wide-7.5	65 a	12.8	83 a	0.4 b	2.5 c	5.7 ab
MAP-narrow-15	67 a	14.3	64 b	0.6 b	3.1 abc	5.1 ab
MAP-wide-15	65 a	15.3	68 b	0.4 b	2.3 bc	5.8 ab
CMAP-narrow-7.5	82 a	15. 8	81 ab	0.5 b	2.5 bc	5.2 ab
CMAP-wide-7.5	75 a	17.2	76 ab	0.5 b	2.4 bc	5.4 ab
CMAP-narrow-15	73 a	17.3	67 b	0.8 ab	3.6 abc	4.8 ab
CMAP-wide-15	68 a	18	75 ab	0.4 b	2.4 bc	6.1 ab
Struvite-narrow-7.5	85 a	10.2	84 a	0.6 b	3.1 bc	4.9 ab
Struvite-wide-7.5	77 a	9.8	77 a	0.5 b	2.9 bc	5.4 ab
Struvite-narrow-15	90 a	11.7	89 a	1.6 a	6.7 a	4.2 b
Struvite-wide-15	87 a	9.3	86 a	0.9 ab	4.2 ab	4.6 ab

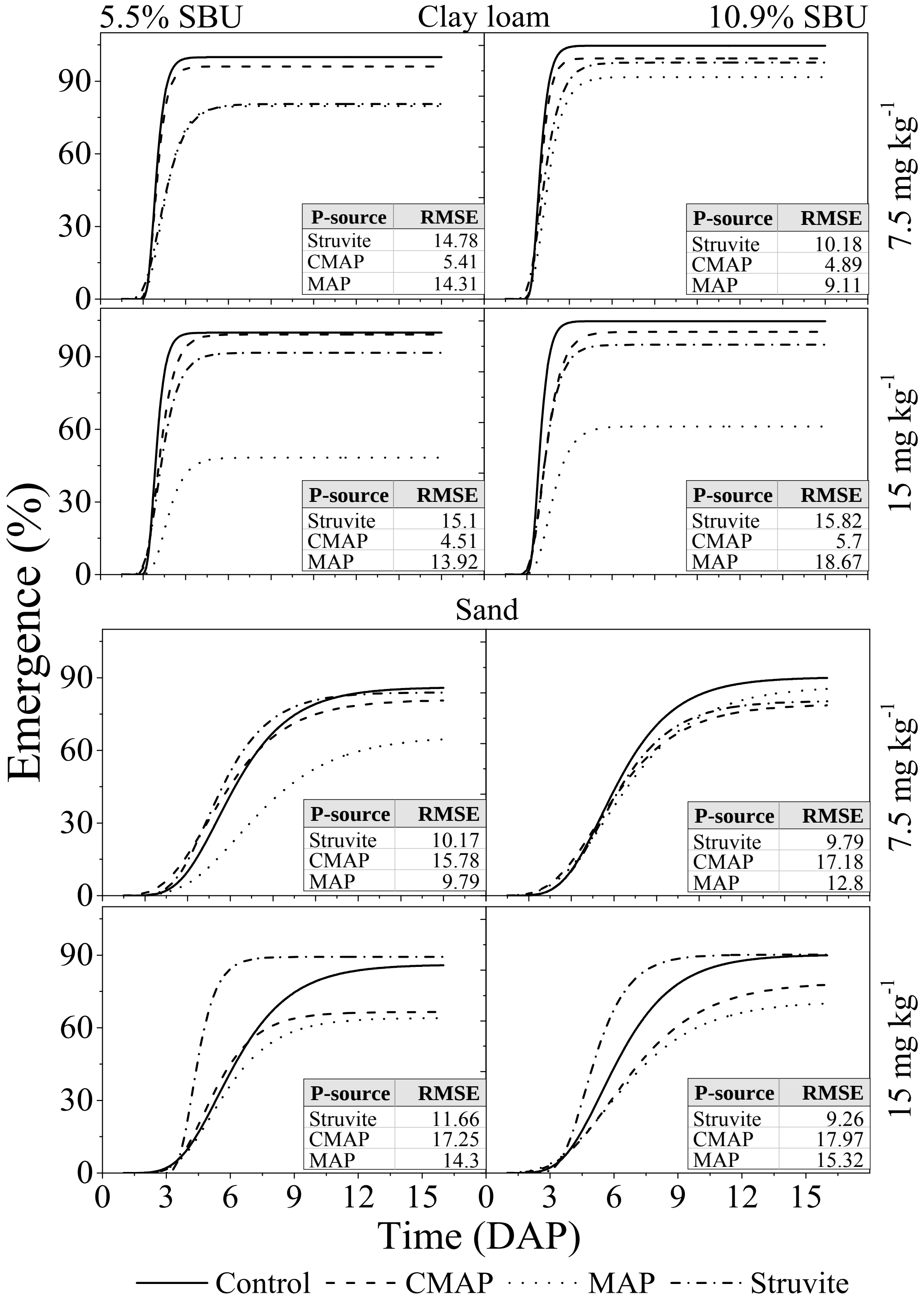
†Narrow and wide; 5.5% and 10.9% SBU, respectively; 7.5 and 15; P rate in mg P kg^{-1}

‡Least squares means of treatments from the ANOVA of final seedling emergence data (Table 3.1)

§Gompertz function parameters M, k, and b represent final emergence (% of seeds planted), mean relative cumulative emergence rate (d^{-1}) and, indirectly, the lag in emergence (b/k) [d (days after planting)], respectively. Numbers in a column within each soil grouping followed by the same letter are not significantly different according to the 95% confidence intervals for M, k, and b, and according to the Tukey method for the lag.

3.4.3.2 Mean Relative Cumulative Emergence Rate. In the clay loam, struvite applied at the 7.5 mg kg^{-1} rate in a narrow band significantly reduced emergence rate (1.5 d^{-1}) relative to the control (3.5 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 1.7 and 3.3 d^{-1} (Table 3.3). For the sand, the narrow-banded 15 mg kg^{-1} rate of struvite (1.6 d^{-1}) significantly improved emergence rate relative to the control (0.5 d^{-1}). Conversely, there were no significant effects of the other treatments on emergence rate relative to the control.

Pairwise-comparisons of the sand treatments only showed that wide-banded struvite at the 15 mg P kg^{-1} rate (0.9 d^{-1}) was not significantly different from all the other struvite treatments. However, the narrow-banded 15 mg kg^{-1} rate of struvite had a significantly faster rate of emergence (16% d^{-1}) than both the narrow-banded (0.6 d^{-1}) and wide-banded (0.5 d^{-1}) 7.5 mg P kg^{-1} rate. Also, the narrow-banded 15 mg P kg^{-1} rate of struvite produced a significantly greater emergence rate (1.6 d^{-1}) than that of MAP (0.6 d^{-1}), but both were not significantly different from that for CMAP (0.8 d^{-1}). However, there were no significant differences in emergence rate among all MAP and CMAP treatments. For all P-sources, there were no significant differences in emergence rate between the SBUs at both rates.



P-source	RMSE
Struvite	14.78
CMAP	5.41
MAP	14.31

P-source	RMSE
Struvite	10.18
CMAP	4.89
MAP	9.11

P-source	RMSE
Struvite	15.1
CMAP	4.51
MAP	13.92

P-source	RMSE
Struvite	15.82
CMAP	5.7
MAP	18.67

P-source	RMSE
Struvite	10.17
CMAP	15.78
MAP	9.79

P-source	RMSE
Struvite	9.79
CMAP	17.18
MAP	12.8

P-source	RMSE
Struvite	11.66
CMAP	17.25
MAP	14.3

P-source	RMSE
Struvite	9.26
CMAP	17.97
MAP	15.32

Figure 3.2 Fitted Gompertz function on canola emergence as affected by P-source, rate, SBU, and soil type. The RMSEs for the controls are, 2.6 for the clay loam and 14.7 for the sand.

3.4.3.3 Lag. Relative to the controls (2.7 d for the clay loam and 6 d for the sand), all treatments did not significantly increase the lag, regardless of soil (Table 3.3). Analysis of variance of the fertilized soils only showed a significant P-source effect (P = 0.01) on the lag (Table 3.4). The time lag for struvite (3.7 d) was significantly shorter than that for MAP (4.3 d), but both were not significantly different from that for CMAP (4 d). There was also a significant soil effect on the lag (P < 0.001). Overall, seedling emergence was significantly faster in the clay loam (2.8 d) than in the sand (5.3 d). There were no significant rate or SBU effects on the duration of the lag.

Table 3.4 Effects of P-source, rate, soil, and SBU on the time taken to reach the point of inflection for cumulative canola seedling emergence

Effect	**Lag**
P-source (P)	
CMAP	4.0
MAP	4.3
Struvite	3.7
Rate (R)	
7.5 mg P kg^{-1}	4.1
15 mg P kg^{-1}	4.0
Soil (S)	
Clay loam	2.8
Sand	5.3
SBU	
5.5 %	3.9
10.9 %	4.1
	P-value†
P	0.006
R	0.28
S	<0.001
SBU	0.17
P × R	0.52
P × S	0.09
P × SBU	0.40
R × S	0.11
R × SBU	0.16
S × SBU	0.12

† Three - and 4-way interactions with P values > 0.1 are not presented.

3.5 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 OC 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 shoot 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 seed germination and/or 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}. However, according to the ANOVA (Section 3.4.2), 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 to the relatively high salt concentrations in the soil solution around MAP granules. Monoammonium phosphate has 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, 2001). 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 on final emergence 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, 2014). The analysis also indicated that when fertilizer was applied at the 15 mg kg^{-1} rate with 5.5% SBU, salt toxicity effects were substantial. Results for the 7.5 mg kg^{-1} rate of struvite are unusual considering that 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 lower water holding capacity and greater hydraulic conductivity of the sand may have reduced the salt toxicity of the added salts as added water may have quickly washed down the fertilizers beyond the seedrow level. The relatively higher CEC and water holding capacity of the clay loam may have contributed to MAP being more restrictive of seedling emergence in this soil than in the sand as the salts may have remained in the seedrow long enough to cause damage. These factors may have reduced the amount of fertilizer salts needed 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) (Ashraf and McNeilly, 2004; Bewley, 1997; Huang and Redmann, 1995). Salts affect cell physiological functions more than water uptake, especially under moisture conditions near optimal (Lindstrom et al., 1976), such as those in this study. The most critical stage may be early embryonic development, just after completion of germination (Bradford, 1990). 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.

These 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; Pace and Benincasa, 2010; Qian and Schoenau, 2010b; Qian et al., 2012; Roberts and Harapiak, 1997). In laboratory studies, Qian and Schoenau (2010b) 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). They reported a decrease in canola emergence > 50% 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.

3.6 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 safer option than MAP when canola is grown in P-deficient soils which require the application 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 yield losses and replanting costs.

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4. OVERALL SYNTHESIS

Nutrient management standards dictate limits for manure application on land as there is concern over P accumulation in soils due to repeated application of large volumes of manure. 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 relatively highly concentrated and economically transportable P-source that also contains N and Mg. The recovered struvite has low solubility or slow release properties, which may enhance crop uptake of P compared with conventional fertilizers. The slow release properties of recovered struvite may also allow seedrow placement of P for salt sensitive crops at higher rates than feasible with conventional fertilizers.

In Chapter 2 of this thesis, the agronomic effectiveness of struvite derived from anaerobically-digested liquid hog manure on canola grown in rotation with spring wheat was evaluated. Canola seedling toxicity following seedrow placement of the struvite compared to monoammonium phosphate (MAP) and polymer-coated MAP (CMAP) was investigated in a separate growth room study (Chapter 3).

The results presented in this thesis show the potential of hog manure-recovered struvite P to improve canola and wheat DMY as effectively as commercial P-sources MAP and CMAP. More importantly, the greater DMY obtained with struvite in later canola crop phases (2 and 3) suggests potential residual benefits from the use of struvite in canola-wheat rotations. This also confirms the slow-release properties of struvite as delayed release of P reduces the exposure of the P to soil P-fixing processes, prolonging the availability of P from struvite. These residual benefits were apparently more important for canola than for wheat, probably due to the greater fertilizer PUE of canola.

However, because of the deficient P status of the soils, the residual benefits from struvite were not enough to significantly improve the residual Olsen P or to eliminate the need to apply more fertilizer P in subsequent crop seasons. Therefore, there is need to assess struvite under field conditions, and through complete crop cycles, to verify these residual benefits. If struvite is indeed beneficial in this regard, then there is potential to improve soil P status, which could be an incentive for adopting the product as an alternative to commercial sources. Also, the effectiveness of the product could encourage the adoption of the struvite recovery technology in the hog industry, which would help ease the problem of hog manure disposal.

Results from Section 3.4 demonstrate a potential for struvite to be applied at a higher rate, which can potentially supply adequate P for canola (Grant and Bailey, 1993) without significant injury to developing seedlings. Canola producers with P-deficient soils that require higher P rates than those recommended for seed-placed MAP can benefit from a P-source such as struvite which can be applied at higher P rates. Despite the ability of canola to compensate for low plant stands (Hocking et al., 2003), using a fertilizer with minimal injury to seedlings is beneficial for curbing costs associated with replanting and loss of yield. Besides salt toxicity from fertilizers, canola yields can be threatened by other stresses such as drought, pests, and diseases. Even under conditions where moisture and temperature are not limiting, such as in the present study, the high rate of MAP caused damage to 50% of the seedlings. Therefore, under field conditions, the ability of the crop to compensate for low plant stands may not be sufficient to avoid yield losses. This is especially important in semi-arid areas such as Manitoba where moisture stress and fertilizer toxicity are common.

4.1 Implications and Recommendations

Results highlighted in this thesis indicate great potential for hog manure-recovered struvite as an effective P-source for canola and wheat. The evidence of beneficial residual effects of struvite observed for DYM in the second and third crop phases (Chapter 2) indicate that struvite may be a viable alternative to the widely used MAP. Similarly, evidence reported in Chapter 3 points to the potential of struvite to alleviate toxicity issues associated with seedrow placement while maintaining P use efficiency and yields in canola-wheat rotations. Importantly, this study demonstrates that struvite can be safely applied at higher P rates than feasible with MAP, an important value for farmers with P-deficient soils, which require higher P rates than those recommended for seedrow placed MAP.

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 water quality issues. If recovered struvite can be widely adopted as a source of P in canola-wheat cropping systems, not only can we address the problem of reliance on finite phosphate rock-derived P-sources and seedling toxicity, which limits the maximum seed-placed P rates, but hog producers will have a viable option to address a major manure disposal challenge that they currently face.

As a follow-up on the promising results reported in this thesis, field experiments should be conducted to provide the basis for sound recommendations to producers and regulators. There is also a need to evaluate struvite for other crops and over a wider range of climatic conditions, STP levels, P rates, and soil texture, to determine specific critical P rates for different conditions.

4.2 References

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5. APPENDICES

Appendix I. Hog Manure-Recovered Struvite

Figure AI.1 Hand-made granules of the hog manure-recovered struvite being evaluated in the bioassays

Appendix II. Greenhouse Bioassay (Chapter 2)

Layout

Figure AII.1 Depiction of the treatment layout for the factorial CRD experimental design used to assess struvite, MAP, and CMAP in a clay loam and sand soil. A third block is not shown in the picture, but, each block comprised of one specific replicate of each treatment.

Results

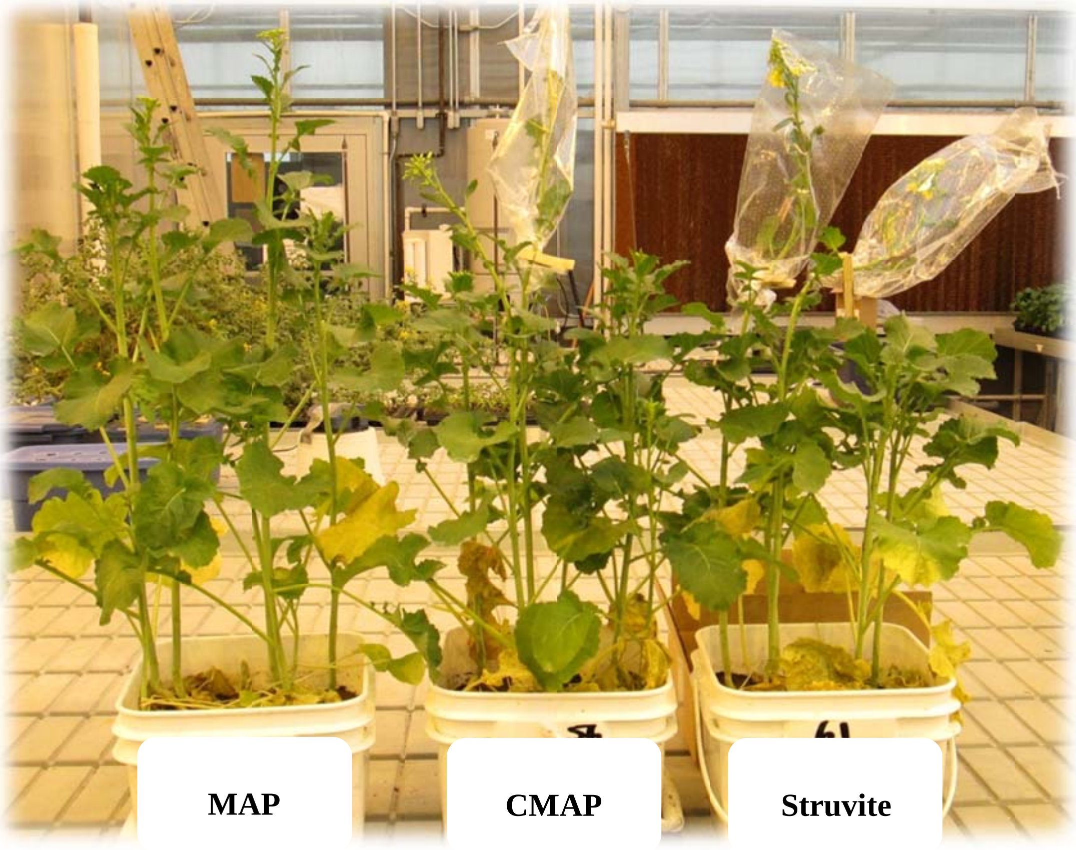

Figure AII.2 Effects of the 15 mg P kg^{-1} rate on canola dry matter at early flowering in the sand soil

Canola and Wheat Responses to Phosphorus Application

Table AII.1 Canola and wheat dry matter yield responses to struvite, MAP, and CMAP application

Treatment†	**Dry Matter Yield (g DM kg^{-1} soil)‡**					
	Canola			**Wheat**		
	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
Clay loam						
Control	0.8 b	1.0 b	0.3 c	1.3 a	1.8 a	1.5 a
CMAP-SB-7.5	2.3 a	2.0 a	0.7 bc	1.5 a	1.8 a	1.8 a
CMAP-SR-7.5	2.2 a	1.8 ab	0.7 bc	2.1 a	1.7 a	1.9 a
CMAP-SB-15	2.1 a	1.8 ab	1.1 abc	1.5 a	1.7 a	2.0 a
CMAP-SR-15	2.5 a	2.1 a	1.3 ab	2.2 a	1.8 a	2.0 a
MAP-SB-7.5	2.1 a	1.8 ab	0.5 bc	1.7 a	2.0 a	1.8 a
MAP-SR-7.5	2.3 a	1.7 ab	0.4 c	1.8 a	1.8 a	1.6 a
MAP-SB-15	2.1 a	2.2 a	1.0 abc	1.9 a	2.0 a	1.7 a
MAP-SR-15	2.7 a	2.1 a	1.3 ab	2.0 a	2.1 a	2.0 a
Struvite-SB-7.5	2.0 a	2.0 a	0.7 bc	1.5 a	1.9 a	1.9 a
Struvite-SR-7.5	2.3 a	2.2 a	0.8 abc	1.5 a	1.7 a	1.8 a
Struvite-SB-15	2.2 a	2.3 a	1.8 a	1.6 a	2.1 a	2.2 a
Struvite-SR-15	2.6 a	2.5 a	1.8 a	2.0 a	1.8 a	2.0 a
Sand						
Control	0.9 b	1.4 a	1.5 a	2.1 ab	1.3 a	1.0 a
CMAP-SB-7.5	2.1 a	1.7 a	1.3 a	1.2 b	0.8 a	0.8 a
CMAP-SR-7.5	2.5 a	1.5 a	1.0 a	1.8 ab	1.1 a	0.9 a
CMAP-SB-15	2.4 a	1.8 a	1.2 a	1.7 ab	1.2 a	1.0 a
CMAP-SR-15	3.0 a	1.4 a	1.2 a	1.9 ab	1.1 a	1.0 a
MAP-SB-7.5	2.4 a	1.4 a	1.4 a	1.9 ab	0.9 a	1.0 a
MAP-SR-7.5	2.8 a	1.4 a	1.2 a	2.3 ab	0.7 a	1.0 a
MAP-SB-15	2.6 a	1.6 a	1.5 a	2.1 ab	1.1 a	1.1 a
MAP-SR-15	2.8 a	1.5 a	1.5 a	2.1 ab	1.1 a	1.2 a
Struvite-SB-7.5	2.2 a	1.5 a	1.4 a	1.9 ab	0.9 a	0.8 a
Struvite-SR-7.5	2.4 a	1.7 a	1.5 a	1.9 ab	0.9 a	0.8 a
Struvite-SB-15	2.5 a	1.9 a	1.5 a	2.1 ab	1.0 a	1.1 a
Struvite-SR-15	2.7 a	1.9 a	1.5 a	1.8 ab	1.1 a	1.0 a

† SB is sidebanding, SR is seedrow, and 7.5 and 15 are P rates in mg P kg^{-1}

‡ Least squares means within each soil and crop phase grouping with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$)

Table AII.2 Canola and wheat phosphorus uptake responses to struvite, MAP, and CMAP application

Treatment†	**P Uptake (mg P kg^{-1} soil)‡**					
		Canola			**Wheat**	
	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
Clay loam						
Control	1.3 b	1.8 a	0.6 a	3.9 a	3.0 a	2.2 a
CMAP-SB-7.5	4.5 a	3.7 a	1.1 a	4.5 a	3.1 a	3.7 a
CMAP-SR-7.5	4.5 a	3.0 a	1.2 a	4.8 a	3.7 a	4.0 a
CMAP-SB-15	6.6 a	3.5 a	1.5 a	5.1 a	3.8 a	3.1 a
CMAP-SR-15	6.1 a	3.9 a	1.8 a	6.4 a	3.9 a	4.0 a
MAP-SB-7.5	4.8 a	2.7 a	1.0 a	4.6 a	4.1 a	3.8 a
MAP-SR-7.5	4.8 a	2.9 a	0.8 a	4.8 a	3.4 a	3.3 a
MAP-SB-15	6.5 a	4.0 a	2.2 a	5.5 a	3.0 a	3.8 a
MAP-SR-15	6.2 a	4.5 a	1.6 a	5.8 a	3.7 a	4.2 a
Struvite-SB-7.5	4.4 a	4.0 a	1.5 a	4.1 a	3.9 a	3.8 a
Struvite-SR-7.5	4.7 a	3.6 a	1.8 a	4.4 a	3.2 a	3.6 a
Struvite-SB-15	6.3 a	4.9 a	2.3 a	4.5 a	4.1 a	3.8 a
Struvite-SR-15	6.8 a	4.6 a	2.8 a	5.0 a	3.4 a	4.1 a
Sand						
Control	1.3 b	2.5 a	2.7 a	1.8 b	1.4 a	1.6 a
CMAP-SB-7.5	4.8 a	3.9 a	2.1 a	4.2 ab	3.0 a	1.3 a
CMAP-SR-7.5	5.2 a	3.1 a	1.7 a	3.3 ab	2.5 a	1.2 a
CMAP-SB-15	7.0 a	3.5 a	2.3 a	5.4 ab	2.7 a	2.5 a
CMAP-SR-15	7.9 a	3.3 a	1.8 a	5.1 ab	2.9 a	2.5 a
MAP-SB-7.5	5.1 a	3.1 a	2.3 a	4.2 ab	1.9 a	1.5 a
MAP-SR-7.5	5.4 a	3.1 a	2.1 a	4.3 ab	1.4 a	1.2 a
MAP-SB-15	8.0 a	3.4 a	2.5 a	5.8 a	2.2 a	1.8 a
MAP-SR-15	7.7 a	2.9 a	2.7 a	5.9 a	2.8 a	2.2 a
Struvite-SB-7.5	4.8 a	3.3 a	1.8 a	3.3 ab	2.1 a	1.0 a
Struvite-SR-7.5	5.0 a	3.9 a	1.7 a	3.6 ab	1.8 a	1.1 a
Struvite-SB-15	7.9 a	3.3 a	2.5 a	4.2 ab	2.3 a	2.6 a
Struvite-SR-15	7.5 a	3.2 a	2.4 a	3.7 ab	2.5 a	1.9 a

† SB is sidebanding, SR is seedrow, and 7.5 and 15 are P rates in mg P kg^{-1}

‡ Least squares means within each soil and crop phase grouping with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$)

Residual Bicarbonate-Extractable Phosphorus Responses

Table AII.3 Residual Olsen P levels in soils after harvesting canola and wheat to struvite, MAP, and CMAP application

Treatment†	Residual Olsen P (mg P kg^{-1} soil)‡					
	Canola			Wheat		
	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
Clay loam						
Control	4.7 c	3.3 b	3.4 a	4.4 b	3.0 a	2.4 a
CMAP-SB-7.5	5.0 bc	4.0 ab	3.8 a	5.3 b	3.2 a	2.8 a
CMAP-SR-7.5	5.6 bc	3.9 ab	3.5 a	5.2 b	3.5 a	2.6 a
CMAP-SB-15	6.4 abc	5.1 ab	3.6 a	6.7 ab	3.7 a	3.3 a
CMAP-SR-15	5.9 abc	5.0 ab	3.6 a	7.7 ab	4.2 a	3.2 a
MAP-SB-7.5	5.1 bc	4.2 ab	3.8 a	6.9 ab	3.4 a	3.1 a
MAP-SR-7.5	5.4 bc	4.7 ab	3.8 a	6.5 ab	3.1 a	2.9 a
MAP-SB-15	6.9 ab	5.2 ab	4.1 a	7.7 ab	4.0 a	3.6 a
MAP-SR-15	7.8 a	5.4 ab	4.1 a	7.8 ab	4.5 a	3.6 a
Struvite-SB-7.5	5.4 bc	4.7 ab	3.6 a	6.7 ab	3.9 a	2.9 a
Struvite-SR-7.5	5.4 bc	4.2 ab	3.6 a	6.7 ab	3.3 a	2.9 a
Struvite-SB-15	7.1 a	5.6 a	4.2 a	9.8 a	4.8 a	3.6 a
Struvite-SR-15	5.9 bc	5.2 ab	3.7 a	9.2 a	3.6 a	3.5 a
Sand						
Control	2.7 c	1.9 a	2.4 a	1.9 b	2.1 a	1.7 a
CMAP-SB-7.5	3.0 bc	2.7 a	2.6 a	3.0 ab	2.3 a	2.6 a
CMAP-SR-7.5	2.7 c	2.7 a	2.8 a	2.8 ab	2.5 a	2.3 a
CMAP-SB-15	3.7 abc	3.3 a	3.0 a	3.9 ab	2.8 a	2.6 a
CMAP-SR-15	3.8 abc	3.2 a	3.2 a	3.7 ab	2.8 a	2.8 a
MAP-SB-7.5	3.2 abc	2.9 a	2.6 a	3.3 ab	2.3 a	2.3 a
MAP-SR-7.5	2.9 bc	2.6 a	2.8 a	3.6 ab	2.2 a	2.5 a
MAP-SB-15	5.0 a	3.8 a	2.8 a	5.4 a	3.3 a	2.8 a
MAP-SR-15	4.9 ab	3.7 a	2.9 a	5.2 a	2.9 a	2.7 a
Struvite-SB-7.5	3.0 bc	2.5 a	2.7 a	2.6 ab	2.2 a	2.0 a
Struvite-SR-7.5	2.7 c	2.6 a	2.8 a	2.7 ab	2.0 a	2.0 a
Struvite-SB-15	3.1 abc	2.8 a	2.6 a	3.1 ab	2.5 a	2.3 a
Struvite-SR-15	3.3 abc	2.9 a	2.6 a	5.9 a	2.4 a	2.4 a

† SB is sidebanding, SR is seedrow, and 7.5 and 15 are P rates in mg P kg^{-1}

‡ Least squares means within each soil and crop phase grouping with the same letter are not significantly different according to the Tukey-Kramer mean comparison procedure ($P > 0.05$)