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REGULAR ARTICLE

Maize and soybean response to phosphorus fertilization with blends of struvite and monoammonium phosphate

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Abstract
Aims Struvite ($MgNH_4PO_4 \cdot 6H_2O$), a low water solubility (<3%) mineral that is increasingly recovered from wastewater treatment plants, has potential to be used as a slow release ammonium phosphate fertilizer, especially when blended with highly water soluble phosphorus (P) fertilizers such as monoammonium phosphate (MAP).
Methods Maize and soybean were fertilized using a gradient of struvite substitution for MAP, entailing five struvite: MAP blends in a factorial combination with struvite granule size (1.5, 3.0 mm diameter) and fertilizer placement (incorporation, banding). Crop biomass, and P and N uptake (total, concentration) were used to evaluate crop response, and post-harvest soil Mehlich-3 P was measured to assess soluble P loss risk.
Results Maize biomass response was similar using up to 50% struvite and similar in soybean using up to 25% struvite. Total P uptake by maize was similar across 0–75% struvite blends, but significantly lower for 100% struvite. Maize apparent fertilizer P uptake and apparent fertilizer P uptake efficiency was greatest for 100% MAP. Despite differences in biomass, soybean apparent fertilizer P uptake and apparent P use efficiency were similar across struvite blends. Soybean P uptake was significantly greater when fertilized with 100% struvite than with 25 and 50% struvite. Inverse correlation of plant P and N concentrations with biomass indicated a biomass dilution effect. Residual soil Mehlich-3 P decreased with increasing struvite substitution of MAP.
Conclusions Struvite:MAP blends (25–50% struvite) appear to lower soluble P loss risk compared to MAP without restricting early season (vegetative) growth of maize and soybean, and this can differ by crop species.

Keywords Magnesium ammonium phosphate · *Zea mays* L. · *Glycine max* L · Mehlich

Abbreviations

P	Phosphorus
N	Nitrogen
MAP	Monoammonium phosphate
AFPU	Apparent fertilizer P uptake
APUE	Apparent P use efficiency

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Introduction

Struvite ($MgNH_4PO_4 \cdot 6H_2O$) is a sparingly water-soluble phosphorus (P) mineral that can be synthesized from diverse P-rich waste streams (e.g., municipal wastewater, manure). Evaluations of the agronomic effectiveness and environmental benefits of struvite relative to commonly used P sources are largely limited to complete substitution of conventional fertilizers by struvite rather than partial substitution (i.e., blends) (Hertzberger et al. 2020; Huygens and Saveyn 2018). Blending struvite with highly water-soluble conventional P fertilizers could potentially provide sufficient early season P while reducing high soil P concentrations that result from the rapid solubilization of P, thereby lowering P loss risk. For example, under simulated rainfall, 21-fold greater runoff P losses from soil fertilized with monoammonium phosphate (MAP) compared to struvite was observed (Everaert et al. 2018). A review of P loss studies ($n = 14$) found that up to 42% of P applied as ammonium phosphates or superphosphates were lost throughout study periods spanning 1–24 weeks (Hart et al. 2004). The authors attributed the losses to the high water solubility of ammonium phosphates and superphosphates, as the greatest losses occurred during the first precipitation event after fertilization. Substituting a proportion of these fertilizers with struvite has the potential to reduce P losses. However, early-season crop P needs may not be met by full substitution of ammonium phosphates or superphosphates with struvite due to its slow dissolution, as was reported for wheat (*Triticum* L.) (Talboys et al. 2016).

Ammonium phosphates may be better suited than superphosphates for struvite blends because they contain a similar N to P ratio as struvite and are more widely utilized in the United States than superphosphates (IFASTAT 2017). Ammonium phosphates account for approximately 88% of P fertilizer sales and thus are the major source of the nearly 3000 Gg P applied to maize (*Zea mays* L.) and soybean (*Glycine max* L.) annually in the United States (USDA-ERS 2018; USDA-NASS 2018a, b). To date, only three studies have quantified the ability of struvite blended with ammonium phosphates or superphosphates to either meet crop P demand or limit P losses, finding that blends supported crop growth or lowered P loss risk compared to ammonium phosphates or superphosphates alone. Wheat P uptake was greatest with 20:80 and 10:90 struvite-diammonium phosphate (DAP) blends compared to 100:0, 30:70, and 0:100, suggesting that an optimum blend contains less struvite than highly water soluble DAP or MAP (Talboys et al. 2016). Ahmed et al. (2016) found root length to be highly correlated ($r^2 = 0.91$) with struvite granule volume loss, with up to 40% greater struvite dissolution and increased length of roots near struvite granules in a 50:50 blend of struvite and triple superphosphate compared to struvite alone. Orthophosphate leaching losses were least under turfgrass (*Cynodon dactylon* L.) fertilized with struvite or a 66:33 blend of struvite-MAP compared to MAP alone (Guertal 2015). Struvite-based fertilizer blends have not been previously evaluated for maize or soybean growth, two major crops grown in the United States. Further evaluations would allow for crop and soil-specific fertilizer recommendations that maximize the agronomic and environmental utility of struvite blends.

The potential of struvite to meet crop P needs remains unclear due to mixed findings from evaluations to-date. Two recent literature reviews found that apparent differences in crop response to struvite compared to ammonium phosphates or superphosphates were minor, but this favorable finding may be due to experimental design flaws (Hertzberger et al. 2020; Huygens and Saveyn 2018). Variable crop responses to struvite was in part due to small soil masses, high soil test P, and excessive P application rates used in greenhouse studies that may have overestimated struvite crop responses. All but two studies evaluating grain crops lacked yield data, a critical metric for assessing fertilizer performance. Though struvite dissolution is increased in the presence of root exudates (Talboys et al. 2016), belowground growth and nutrient uptake was not measured, likely leading to the lower apparent P use efficiency reported for crops fertilized with struvite.

Two overlooked factors in evaluations of struvite are granule size and placement, both of which stand to influence struvite dissolution and P availability. Granule size is likely to affect struvite solubilization due to surface area effects on dissolution. The larger specific surface area of smaller granules allows for greater interactions with soil, water, and root-exuded organic acids (e.g., citrate, oxalate, malate), all of which expedite struvite dissolution (Talboys et al. 2016). For instance, finely ground (< 0.15 mm) struvite has been found to fully solubilize in soil over 28 days compared to only 50% when applied as 2.4 mm diameter granules (Degryse et al. 2017). Because ammonium phosphate fertilizers are applied in granular form, the use of ground struvite is less attractive for agricultural producers since this would require alternative application implements. To date, crop growth studies have evaluated either fine-sized or ground struvite (< 0.5 mm) or granules $\geq$2.3 mm diameter (Hertzberger et al. 2020). The slower dissolution of larger struvite granules may be less able to meet early-season P needs than smaller struvite granules. Blends of struvite with highly water soluble P fertilizers may lessen this limitation to early crop growth by providing sufficient P from the rapidly solubilized non-struvite P source. Quantifying crop responses to struvite granule size when blended with another P fertilizer can identify how granule size influences optimization of crop growth and P loss risk mitigation.

The placement of struvite-ammonium phosphate blends is likely to influence crop P uptake due to differences in root distribution and root proximity engendered by incorporation versus banding. Incorporated broadcast applications distribute fertilizer granules uniformly across the soil surface depth whereas the banding of P fertilizer entails its placement below the seed in a concentrated zone, generally increasing P uptake efficiency compared to broadcasting (Malhi et al. 2001). For example, banding triple superphosphate increased maize yields by 3–4% in a strip-till system compared to broadcasting in a no-till system (Fernández and White 2012). Conversely, deep banding (15 cm depth) of granulated P did not significantly increase maize yields compared to broadcasting over a 10-year period (Preston et al. 2019). However, apparent P use efficiency (APUE) tends to be higher under banding (30–35%) compared to broadcasting (5–10%) (Preston et al. 2019). Quantification of differences in crop-specific responses to the proportion of struvite in blends, granule size, and fertilizer placement can identify the degree of MAP substitution with struvite that maximizes crop growth potential of struvite: MAP blends.

The objectives of this greenhouse study were 1) to quantify the effects of five struvite: MAP blends, struvite granule size, and placement on maize and soybean biomass and P uptake to determine the optimum struvite: MAP blends and their management, and 2) to evaluate the effect of the struvite: MAP blends on soil Mehlich-3 P. It was hypothesized that an increasing proportion of struvite would lead to early season P deficiency and therefore less P uptake and crop biomass. Crop growth and P uptake were expected to be lower for larger struvite granules (3.0 vs. 1.5 mm diameter) because struvite solubilization is affected by specific surface area and thus soil solution contact. Compared to incorporation, subsurface placement of struvite simulating in-field banding was hypothesized to increase apparent fertilizer P uptake (AFPU) and APUE due to greater proximity of fertilizer granules to roots. Loss risk of P, assessed by differences in residual (post-plant removal) soil Mehlich-3 P at three depths, were hypothesized to increase with the proportion of MAP in the fertilizer blends due to the greater water solubility of MAP relative to struvite.

Materials and methods

Experimental design

Two greenhouse experiments were performed to assess the early season agronomic effectiveness of struvite-MAP blends for maize and soybean, and the impact of blends on residual soil Mehlich-3 P. The 0–30 cm depth of the A_p horizon of a fine, smectitic, mesic Aquic Argiudoll (Flanagan series) was harvested from the University of Illinois South Farms (40.083°N, 88.225°W), air dried and sieved to <4 mm. The soil had a cation exchange capacity of 28.8 meq 100 g^{-1}, 2.6% total organic C, 12.5 C:N, and pH 5.6 (1:1 m/v in H_2O). The Flanagan and related soil series (e.g., Drummer series: fine-silty, mixed, superactive, mesic Typic Endoaquolls) have a mapped extent of >1.5 million ha across north-central Illinois (NRCS 2019). Soil test P was colorimetrically determined as molybdate-reactive phosphate extracted by Mehlich-3 solution (Mehlich 1984) using subsamples of composited soil (<2 mm, $n = 10$) was 19.0 ± 1.2 mg P kg^{-1} soil, which is slightly below the critical value of 20–25 mg kg^{-1} in the surface 17.8 cm depth (i.e., 7 in) recommended for Illinois maize and soybean production (Fernández and Hoeft 2009).

Ratios of struvite to MAP used for P treatments were 100:0 (S100:M0), 75:25 (S75:M25), 50:50 (S50:M50), 25:75 (S25:M75), and 0:100 (S0:M100) to quantify crop responses across a full gradient of MAP substitution with struvite. Commercial struvite fertilizer (Crystal Green; 5.0% N, 12.2% P; 1.5; 3.0 mm diameter) was obtained from Ostara Nutrient Recovery Technologies Inc. (Vancouver, Canada) and MAP (11% N, 22.7% P; 3.0 mm diameter) was obtained from Illini FS (Tolono, IL, USA). To control for differences in NH_4^+-N among MAP-struvite blends, NH_4Cl was added to achieve the same NH_4^+-N rate as the 100% MAP treatment (12.0 mg kg^{-1}). Phosphorus application rates were calculated based on a 15.2 cm soil depth, soil mass of 9.33 kg within this depth, a Mehlich-3 P concentration of 19.0 mg kg^{-1}, and grain P removal rates of 2.91 g P kg^{-1} for maize and 5.50 g P kg^{-1} for soybean (Villamil et al. 2019) assuming common yields in central Illinois of 12.6 Mg ha^{-1} for maize and 4 Mg ha^{-1} for soybean (USDA-NASS 2018a, b). Since soil test P was considered below optimum for maize and soybean for this region (Fernández and Hoeft 2009), to reflect producer practices a buildup P rate was included to target a post-harvest soil Mehlich-3 P concentration of 22.5 mg P kg^{-1}. The P rate applied to maize was 28.4 mg P kg^{-1}, corresponding to a total of 265 mg P per container or a field rate of 51.9 kg P ha^{-1}. The P application rate for soybean was 20.6 mg P kg^{-1}, equivalent to 192 mg P per container or 37.7 kg P ha^{-1}. To ensure nitrogen (N) was not limiting to maize growth, which can confound attribution of crop growth responses to a P effect of struvite (Hertzberger et al. 2020), additional N was applied at the vegetative stage with two fully developed leaf collars (V2) (Hanway 1963) to mimic an N sidedress of 1258.9 mg N in the form of 28% urea ammonium nitrate (UAN) per container (189 kg N ha^{-1}) by pipet in a 15.2 cm diameter circle on the soil surface. Additional N was not added to soils used to grow soybean, as soybean does not generally respond to N fertilization in the North Central US region (Baker and Sawyer 2005; Fernández 2009). Total N from fertilizer blends and UAN sidedress was applied to all maize at a field-equivalent rate of 189.4 kg N ha^{-1} or 1382 mg N per container. This economically optimum N rate was determined from the Corn Nitrogen Rate Calculator for central Illinois (Iowa State 2009).

Fertilizer was either incorporated (mixed throughout the upper 7.6 cm of soil) or banded (placed along the circumference of a 5.1 cm diameter circle centered 5.1 cm below the seed), using either 1.5 or 3.0 mm diameter struvite granules. A P-unfertilized control (P0) receiving the same N and potassium (K) application rate as the P-fertilized treatments was included in each block in order to calculate AFPU and thus APUE for each P-fertilized treatment. Containers were arranged in a randomized complete block design with 4 replications for a total of 84 containers per crop species. Cylindrical containers with a diameter of 30.5 cm and a height of 30.5 cm were used to minimize root binding, which may overestimate solubilization of struvite (Hertzberger et al. 2020). Containers were filled to 22.8 cm height with 14.00 kg air dried soil (<4 mm) at 0.04 g g^{-1} gravimetric water content, corresponding to 13.44 kg oven dry soil with a bulk density of 1.20 g cm^{-3}.

Soil moisture was maintained at 40% of water holding capacity (≈ 60 g 100 g^{-1} soil) by watering as needed, generally daily or every other day. Three seeds of maize (Dekalb DKC62–08) or soybean (Asgrow AG34X6) were placed at 2.5 cm depth and thinned to one plant per container 6 days after emergence. To address a potential K deficiency that began to visually manifest at V2 stage, 6.0 g KCl (153 kg K ha^{-1}) was surface applied as a fine powder (<0.1 mm diameter) to each container.

Sampling and analyses

All aboveground and belowground biomass was harvested when plants receiving 100% MAP were at the V12 growth stage for maize (44 d) and R1 for soybean (45 d). These growth stages reflect key development points of these two crops, specifically the transition from vegetative (V) growth to reproductive (R) growth (Bender et al. 2012, 2015). This transition occurs from V12/VT to R1 in maize (Karlen et al. 1988), and from a variable (cultivar-dependent) late-stage V to R1 for soybean (Hanway and Thompson 1967). Aboveground maize biomass was separated into stalk and leaf biomass fractions, and aboveground soybean biomass was analyzed as a single sample. Aboveground and belowground dry biomass was determined by drying samples at 60 °C to constant mass (72 h). Soils were sampled at biomass harvest at three 7.6 cm depth increments of 0–7.6, 7.6–15.2, and 15.2–22.8 cm.

Plant nutrient concentrations and total uptake

Ground aboveground biomass samples (<2 mm) were analyzed for P and Mg concentrations by Brookside Laboratories, Inc. (New Brennen, OH) by nitric acid digestion and inductively coupled plasma optical emission spectrometry (ICP-OES). Belowground biomass was analyzed for total P concentration by nitric acid digestion followed by molybdate colorimetry. All biomass samples were analyzed for total N concentration by dry combustion chromatography. Total uptake of a nutrient element was calculated by normalizing concentration for total dry biomass (Eq. 1).

$$\begin{aligned} &\textit{total uptake}\ (mg) \\ &\quad = \textit{nutrient concentration}\ \left(mg\ g^{-1}\right) \\ &\qquad \times \textit{dry biomass}(g) \end{aligned} \tag{1}$$

Apparent fertilizer P uptake (AFPU) was calculated as the difference in P uptake from fertilized treatments and the average P uptake from P0 treatments (Eq. 2).

$$AFPU = total\ P\ uptake\ (fertilized\ treatment) - total\ P\ uptake\ (0P\ treatment) \quad (2)$$

Apparent P use efficiency (APUE) was calculated by dividing AFPU by the total P fertilizer application of 265 mg P per maize plant and 192 mg P per soybean plant (Eq. 3).

$$PUE = \frac{APU\ (mg\ P)}{mg\ P\ applied\ pot^{-1}} \quad (3)$$

Soil P and N

Soil test P was determined as colorimetric Mehlich-3 P at each of the three depths of 0–7.6, 7.6–15.2 and 15.2–22.8 cm. Soils were carefully evaluated during processing to avoid any visible particulate struvite from being ground to pass a < 2 mm sieve, as residual struvite could artificially increase apparent Mehlich-3 P concentrations due to dissolution in the acidic extraction solution (pH < 3) (Mehlich 1984). Duplicate 3 g air dried equivalent soil (<2 mm sieved) were extracted with 30 mL Mehlich-3 solution by horizontal shaking at 150 rpm for 5 min, followed by filtration (Whatman #1; 11 μm pore) (Mehlich 1984) and colorimetric quantification of molybdate-reactive orthophosphate (Murphy and Riley 1962). Soil extractable NH_4^+ and NO_3^- were determined by extracting 6 g air-dried equivalent soil samples (<2 mm sieved) in duplicate with 30 mL of 2 M KCl by horizontal shaking at 150 rpm for 1 h and filtering (Whatman #1; 11 μm pore). Extracts were analyzed colorimetrically for NH_4^+-N using the salicylate-hypochlorite method (Verdouw et al. 1978) and for NO_3^--N by vanadium (III) chloride reduction (Doane and Horwath 2003).

Statistical analyses

Data met assumptions of normality and homogeneity of variances, and were analyzed in SAS 9.4™ using the GLIMMIX procedure. All two and three-way interactions of fixed effects were non-significant for each response variable and thus were analyzed separately. Simple t-tests were used for least squares mean separations to identify significant differences between treatments (struvite-MAP blend, granule size, placement) at $\alpha = 0.05$.

Results

Crop growth

There was a marked crop-specific biomass response to P fertilization with struvite: MAP blends. Overall, total, aboveground and belowground biomasses were inversely related to the proportion of struvite in the fertilizer blends (Fig. 1). In V12 maize, statistically similar biomass (total, aboveground and belowground) was obtained with up to 50% substitution of MAP by struvite (Fig. 1a). Aboveground and belowground (i.e., root) biomass decreased notably as struvite proportionality increased above 50%. Maize fertilized with 100% struvite generated 22% less total biomass ($p < 0.0001$), 27% less aboveground biomass ($p < 0.0001$), and 40% less root biomass ($p < 0.0001$) than when fertilized with 100% MAP. For soybean, statistically similar total ($p = 0.4144$) and aboveground ($p = 0.2629$) biomass were observed with up to 25% struvite, and root biomass ($p > 0.83$) was similiar with up to 50% struvite (Fig. 1b). Relative to MAP, total soybean biomass was lower by 19% ($p < 0.0001$) and soybean root biomass was lower by 22% ($p = 0.0104$) with 100% struvite. All P-fertilized plants had greater biomass than the P0 control except for soybeans fertilized with 100% struvite, confirming that maize was P limited in this soil and biomass responses were influenced by P availability. Granule size and placement did not influence maize biomass ($p = 0.052$ and 0.206, respectively), nor did granule size influence soybean biomass ($p = 0.464$). Fertilizer placement had an effect on soybean biomass ($p = 0.002$) with slightly greater total biomass when fertilizer was banded (24.6 g) compared to incorporated (23.2 g).

The proportion of total biomass contributed by roots ranged 17–26% for maize and 15–16% for soybean (Table 1). Maize root biomass to aboveground biomass ratios declined with increasing proportion of struvite in blends, and the lowest root: aboveground biomass occurred without P fertilization. There were no differences in soybean root:aboveground biomass across struvite: MAP blends (all possible comparisons $p > 0.25$).

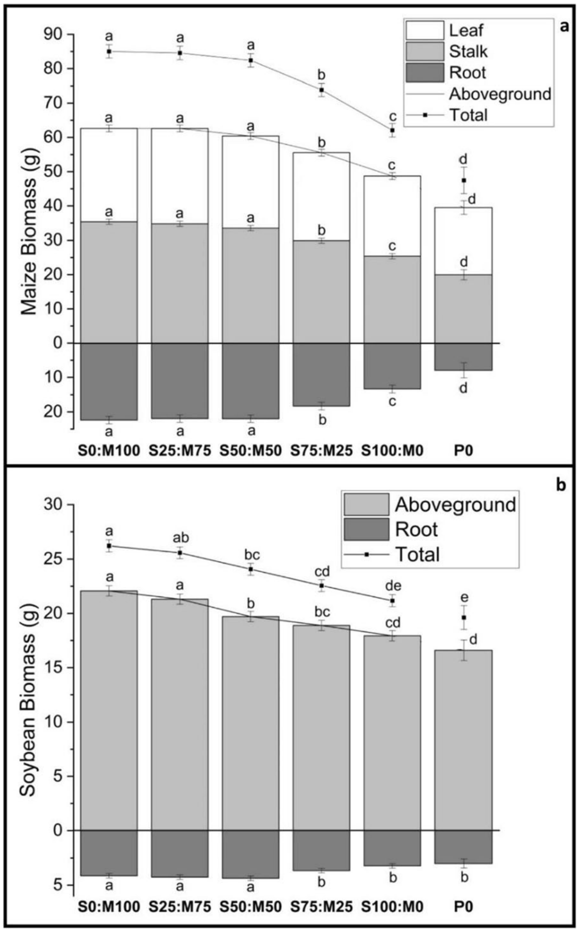

Fig. 1 Total, aboveground, and belowground biomass of (**a**) V12 maize and (**b**) R1 soybean grown using struvite (S), monoammonium phosphate (M), S: M blends, and an unfertilized (P0) control. Means with the same letter are not significantly different at $\alpha = 0.05$

Table 1 Ratio of root and aboveground biomass for V12 maize and R1 soybean for blends of struvite (S) and monoammonium phosphate (M), as well as a P-unfertilized control (P0)

Treatment	Maize	Soybean
S0:M100	0.36 (0.016) a	0.19 (0.011) a
S25:M75	0.35 (0.016) a	0.20 (0.011) a
S50:M50	0.36 (0.016) a	0.22 (0.011) a
S75:M25	0.33 (0.016) a	0.19 (0.011) a
S100:M0	0.27 (0.016) b	0.18 (0.011) a
P0	0.20 (0.031) b	0.18 (0.023) a

Means with the same letter are not significantly different at $\alpha =$ 0.05. Values in parentheses denote the standard error

Crop P and N uptake

Maize and soybean P uptake (mg plant^{-1}) did not necessarily reflect the trends in biomass. Aboveground P uptake was similar across P treatments in maize whereas total P uptake and belowground (root) uptake were inversely related to the degree of struvite substitution for MAP (Fig. 2a). Maize fertilized with 100% struvite had 8% lower total P uptake ($p = 0.051$) and 6% total N uptake ($p = 0.010$) than maize that received 100% MAP. Soybean P uptake across the struvite substitution gradient did not reflect aboveground or belowground biomass (Fig. 2b). Total soybean P uptake was significantly lower for plants receiving 25% and 50% struvite than for those fertilized with 100% struvite ($p < 0.05$). There was no difference in total P uptake ($p = 0.87$) or total N uptake ($p = 1.00$) between soybean fertilized with 100% struvite and 100% MAP. Total N uptake in soybean appeared to be unrelated to P uptake (Fig. 2).

Apparent fertilizer P uptake (AFPU) and apparent P use efficiency (APUE) of maize were inversely related to the proportion of struvite substitution for MAP (Table 2). Confidence intervals suggested a significant difference in maize AFPU (35.1 vs 25.2 mg P) and APUE (13.2% vs 9.5%) between 100% MAP and 100% struvite treatments. There was no difference among blends for soybean AFPU and APUE, further suggesting maize was more responsive to P fertilization than soybean for this soil. Confidence intervals encompassed zero for soybean AFPU and APUE, indicating no significant difference in P uptake by soybean among struvite: MAP blends relative to P-unfertilized soybean.

There was no effect of struvite granule size or placement on crop biomass nutrient concentrations ($p > 0.05$). Maize and soybean P and N concentrations indicated a biomass dilution effect in which concentrations were lowest for plants with greatest biomass (Tables 3 and 4). Maize ($p < 0.001$) and soybean ($p < 0.001$) aboveground P concentrations were higher in plants receiving 100% struvite relative to those receiving 100% MAP, but the opposite was true for aboveground biomass. Aboveground P concentrations of maize and soybean were both 28% higher under fertilization with 100% struvite relative to 100% MAP, whereas 100% MAP yielded 22% greater maize biomass and 19% greater soybean biomass relative to 100% struvite. Root P concentrations were similar

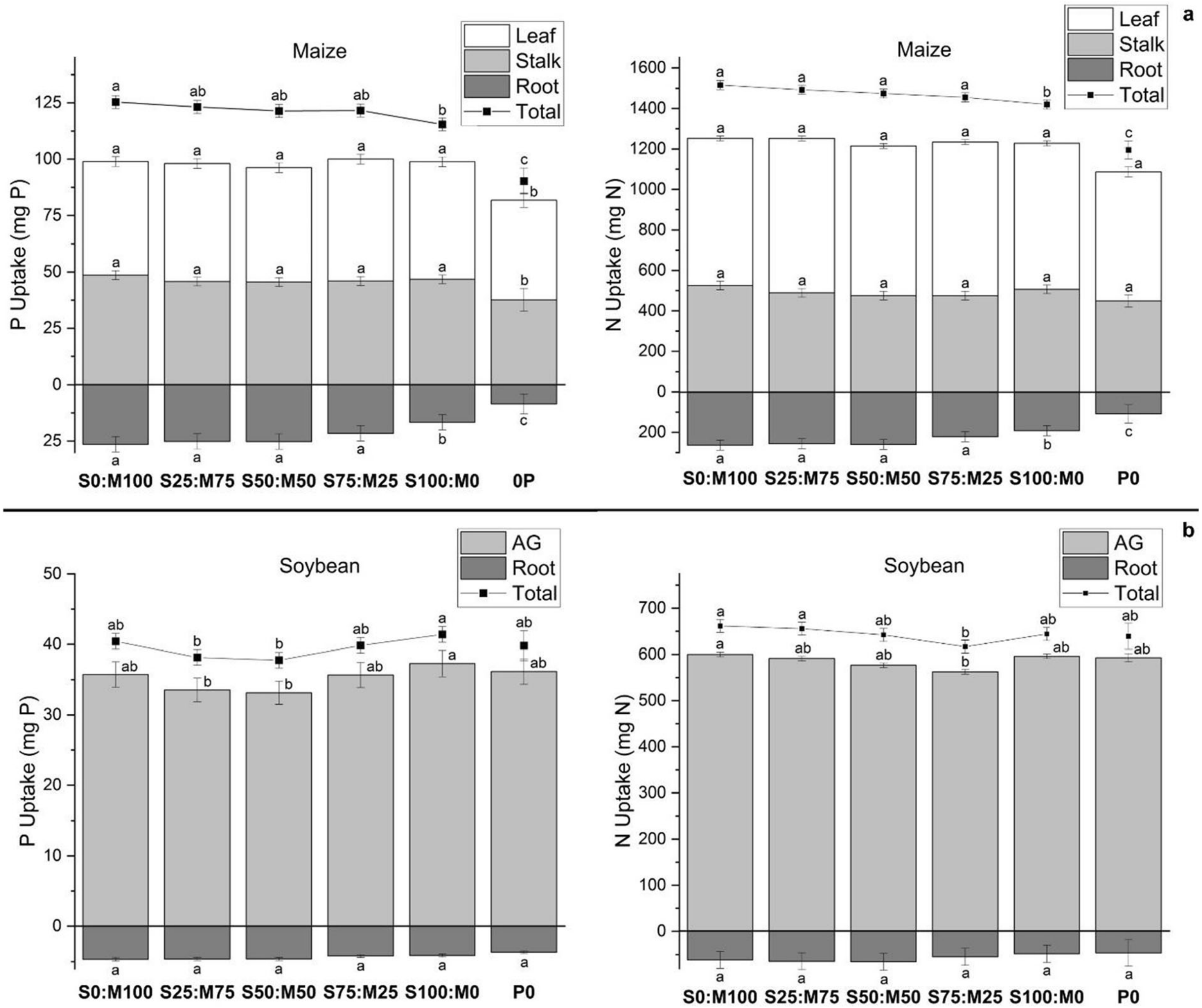

Fig. 2 Total, shoot, leaf, and root P and N uptake for V12 maize and aboveground and root P and N uptake for (**b**) R1 soybean fertilized with struvite (S), monoammonium phosphate (M), S: M blends, and a P-unfertilized control (P0). Means with the same letter are not significantly different at $\alpha = 0.05$

across all fertilizer blends in maize and soybean ($p > 0.05$). Soybean root biomass exhibited a 25% difference in P concentration between 100% struvite and 100% MAP and a 26.7% difference in maize. Maize aboveground biomass N concentration at 100% struvite was 24.6% higher relative to 100% MAP, and soybean aboveground N concentrations were 22.3% higher at 100% struvite. The difference in total N concentration between 100% struvite and 100% MAP was 26.4% for maize and 20.5% for soybean. Maize root N concentrations were elevated by 20% with fertilization using 100% struvite compared to 100% MAP. However, soybean root N concentration was similar across struvite: MAP blends ($p > 0.05$). Differences in maize (8.7%) and soybean (7.1%) aboveground Mg concentration between 100% MAP and 100% struvite were not as pronounced as for P and N concentrations.

Soil P and N

Post-harvest Mehlich-3 P was similar across fertilizer treatment and crop species at each of the three measured depths (Fig. 3a-c) and on average was 50% lower than at the start of the experiment. Mehlich-3 P averaged across depths for soils used to grow both crop species was 14%

Table 2 Apparent fertilizer P uptake (AFPU) and apparent P use efficiency (APUE) means and 95% confidence range for V12 maize and R1 soybean by P treatment of struvite (S), monoammonium phosphate (M), and S: M blends

Treatment	AFPU (mg plant^{-1})	AFPU 95% Confidence Range (mg plant^{-1})	APUE (%)	APUE 95% Confidence Range (%)
Maize				
S0:M100	35.07	29.7–40.5	13.2	11.2% - 15.3
S25:M75	32.90	27.5–38.3	12.4	10.4% - 14.5
S50:M50	31.13	25.7–36.5	11.7	9.7% - 13.8
S75:M25	31.32	25.9–36.7	11.8	9.8% - 13.9
S100:M0	25.15	19.7–30.5	9.5	7.5% - 11.5
Soybean				
S0:M100	0.61	−3.42 - 4.64	0.3	−1.8% - 2.4
S25:M75	−1.65	−2.44 - 5.62	−0.9	−3.0% - 1.2
S50:M50	−1.63	−5.68 - 2.37	−0.8	−3.0% - 1.3
S75:M25	0.04	−5.66 - 2.40	0.0	−2.1% - 2.1
S100:M0	1.59	−3.99 - 4.07	0.8	−1.3% - 2.9

greater (10.4 vs 9.0 mg kg^{-1}) for MAP, S25:M75, and S50:M50 (Fig. 3d).

The effects of struvite granule size ($p = 0.04$) and the interaction of fertilizer treatment and granule size (<0.001) were significant for Mehlich-3 P in maize (Table 5). Mean Mehlich-3 P for soils fertilized with 25 to 100% struvite blends was 9.4, 10.9, 9.6, and 9.7 mg P kg^{-1} for 1.5 mm diameter struvite granules and 10.9, 9.5, 8.6, and 8.5 mg P kg^{-1} for 3.0 mm diameter granules. Except for the S25:M75 blend treatment, for which Mehlich-3 P was significantly greater for the 3.0 mm versus 1.5 mm diameter granules, Mehlich-3 P for the smaller struvite granules was significantly greater across the struvite substitution gradient.

Extractable NH_4^+-N concentrations were nearly 2-fold greater in soils used for maize than for soybean, and extractable NO_3^--N concentrations were similar between crop species (Table 6). In soil used to grow maize, NH_4^+-N concentrations at the middle and bottom depths were double those of the top depth. Ammonium-N concentrations were not influenced by the degree of struvite substitution for MAP, including extremes of 100% struvite or MAP. Nitrate-N concentrations increased with soil depth and were greatest in the P-unfertilized control followed by 100% struvite in soils used to grow maize. For soils used to grow soybean, which was not N fertilized, nitrate-N concentrations were on average 8% lower at 7.6–15.2 cm depth, and mean NO_3^--N concentrations were greatest in the P-unfertilized control.

Discussion

Crop growth and nutrient uptake

For both maize and soybean, the decline in total biomass with greater proportions of struvite in struvite: MAP blends supports the hypothesized limitation of early season crop growth with greater proportions of struvite due to a lack of P availability. Maize total biomass was similar with up to 50% substitution of MAP by struvite and soybean total biomass was similar with up to 25% struvite substitution. The greater sensitivity of soybean growth to the degree of struvite substitution for MAP may be a result of soybean generally having 52% less root biomass and 22% less root length than maize (Hopkins and Hansen 2019), consistent with the 50–75% lower root biomass of soybean compared to maize in the present study. Less root biomass and length will likely limit root solubilization of struvite by rhizosphere acidification and/or exudation. Differences in root biomass observed here may be less pronounced in the field, as a recent meta-analysis found maize root biomass per unit area in the field to be 25% greater than soybean (weighted dry biomass mass average to 0–60 cm depth) (Ordonez et al. 2018). Establishing a root system in the early growth stages is vital for nutrient acquisition and yield potential of any plant (Pimentel et al. 1995; Grant et al. 2001; Flaval et al. 2014). Under nutrient limited conditions, crops allocate photosynthate belowground for nutrient acquisition strategies such as root growth

Table 3 Nutrient element concentrations of maize biomass harvested at V12 stage fertilized with struvite (S), monoammonium phosphate (M), and S: M blends, as well as a P-unfertilized control (P0)

Treatment	Leaf	Stalk	Aboveground	Root	Total
Phosphorus (mg g^{-1} dry mass)					
S0:M100	1.8 b	1.4 c	1.6 c	1.2 a	1.5 c
S25:M75	1.9 (1.8%) b	1.3 (−4.4%) c	1.6 (−0.9%) c	1.1 (−8.3%) a	1.5 (0.0%) c
S50:M50	1.9 (2.1%) b	1.4 (−1.2%) c	1.6 (0.8%) c	1.1 (−8.3%) a	1.5 (0.0%) c
S75:M25	2.1 (14.3%) a	1.5 (11.8%) b	1.8 (14.0%) b	1.2 (0.0%) a	1.7 (13.3%) b
S100:M0	2.2 (20.9%) a	1.8 (34.1%) a	2.0 (28.4%) a	1.2 (0.0%) a	1.9 (26.7%) a
P0	2.3 (22.3%) a	1.9 (37.2%) a	2.1 (31.0%) a	1.1 (−8.3%) a	1.9 (26.7%) a
Nitrogen (mg g^{-1} dry mass)					
S0:M100	26.8 c	15.3 d	20.3 d	12.0 b	18.2 d
S25:M75	27.4 (2.2%) c	14.3 (−6.5%) d	20.1 (−1.0%) d	11.9 (−0.8%) b	18.1 (−0.5%) d
S50:M50	27.6 (3.0%) c	14.3 (−6.5%) d	20.2 (−0.5%) d	11.9 (−0.8%) b	18.1 (−0.5%) d
S75:M25	29.7 (10.8%) b	16.1 (5.2%) c	22.4 (10.3%) c	12.3 (2.5%) b	19.9 (9.3%) c
S100:M0	31.0 (15.7%) ab	20.1 (31.4%) b	25.3 (24.6%) b	14.4 (20.0) a	23.0 (26.4%) b
P0	32.6 (21.6%) a	23.0 (50.3%) a	27.7 (36.5%) a	13.5 (12.5%) ab	25.3 (39.0%) a
Magnesium (mg g^{-1} dry mass)					
S0:M100	2.2 a	2.3 cd	2.3 bc		
S25:M75	2.2 (0.0%) a	2.2 (−4.3%) d	2.2 (−4.3%) c		
S50:M50	2.3 (4.5%) a	2.2 (−4.3%) d	2.2 (−4.3%) c		
S75:M25	2.3 (4.5%) a	2.4 (4.3%) c	2.4 (4.3%) b		
S100:M0	2.2 (0.0%) a	2.8 (21.7%) b	2.5 (8.7%) a		
P0	2.3 (4.5%) a	3.1 (34.8%) a	2.7 (17.4%) a		

Means with the same letter are not significantly different at $\alpha = 0.05$. Values in parentheses denote the percent difference compared with the MAP treatment

and exudate production (Talboys et al. 2016), though the effect of P deficiency on root growth is species specific. Maize tends to have larger root-to-shoot ratios and roots that more readily proliferate in response to P deficiency compared to soybean (Lyu et al. 2016). Additionally, organic acids such as citrate exuded by roots and that can increase struvite dissolution are positively correlated with root biomass and root surface area (Eisenhauer et al. 2017; Guyonnet et al. 2018). The P required to develop root structures during early growth stages means that P limitation may have ameliorated the proposed root exudate driven solubilization of struvite (Talboys et al. 2016), thereby leading to the observed lower biomass in both crops with increasing proportions of struvite.

The proportion of root biomass relative to shoot biomass increased for maize but not soybean in the struvite-only and the P0 treatments. As low soil P availability generally increases the root-to-shoot biomass ratio (Lynch 2015), including maize (Anghinoni and Barber 1980; Mollier and Pellerin 1999), this suggests that struvite's low solubility may induce P-deficiency plant responses even when applied at agronomically appropriate rates. Because plants exhibit greater plasticity in root morphology than in shifting root vs shoot biomass allocation to address nutrient deficiencies (Poorter and Ryser 2015), our evaluation of root biomass may have missed morphological responses such as root fineness and length (Wen et al. 2017) across the gradient of struvite substitution. On the other hand, changes in root vs shoot biomass allocation under low soil P conditions are complex and vary by crop growth stage, with shifts occurring for maize (e.g., Anghinoni and Barber 1980) and soybean (e.g., Fredeen et al. 1989) in early vegetative growth. Similar root versus shoot biomass and P uptake of soybean even without P fertilization is consistent with lower P demand for soybean relative to maize at their respective growth stages (Bender et al. 2012, 2015) and greater soil P acquisition efficiency of soybean (Li et al. 2007; Fernández et al. 2009). Though generally greater

Table 4 Nutrient concentrations of soybean biomass harvested at R1 stage fertilized with struvite (S), monoammonium phosphate (M), and S: M blends, as well as a P-unfertilized control (P0)

Phosphorus (mg g^{-1} dry mass)			
Treatment	Aboveground	Root	Total
S0:M100	1.6 c	1.1 a	1.6 c
S25:M75	1.6 (−2.8%) c	1.1 (0.0%) a	1.5 (−6.3%) c
S50:M50	1.7 (3.9%) c	1.1 (0.0%) a	1.6 (0.0%) c
S75:M25	1.9 (16.6%) b	1.2 (9.1%) a	1.8 (12.5%) b
S100:M0	2.1 (28.4%) a	1.3 (18.2%) a	2.0 (25.0%) a
P0	2.2 (34.5%) a	1.2 (9.1%) a	2.1 (31.3%) a
Nitrogen (mg g^{-1} dry mass)			
Treatment	Aboveground	Root	Total
S0:M100	27.4 c	14.7 a	25.4 d
S25:M75	27.9 (1.8%) bc	14.9 (1.4%) a	25.7 (1.2%) cd
S50:M50	29.5 (7.7%) bc	15.0 (2.0%) a	26.9 (5.9%) cd
S75:M25	30.0 (9.5%) b	14.5 (−1.4%) a	27.6 (8.7%) bc
S100:M0	33.5 (22.3%) a	14.8 (0.7%) a	30.6 (20.5%) a
P0	35.9 (31.0%) a	15.2 (3.4%) a	32.8 (29.1%) a
Magnesium (mg g^{-1} dry mass)			
Treatment	Aboveground		
S0:M100	4.2 ab		
S25:M75	4.1 (−2.4%) c		
S50:M50	4.2 (0.0%) bc		
S75:M25	4.4 (4.8%) ab		
S100:M0	4.5 (7.1%) a		
P0	4.6 (9.5%) a		

Means with the same letter are not significantly different at $\alpha = 0.05$. Values in parentheses denote the percent difference compared with the MAP treatment

tolerance of legumes than non-legumes has been reported for low water solubility P minerals such as phosphate rock due to stronger rhizosphere acidification (Aguilar and van Diest 1981), soybean biomass in our study was more sensitive to increased struvite substitution of MAP. One way to reconcile these contrasting results is that the greater rhizosphere acidification of soybean relative to maize implicated in dissolution of sparingly soluble P minerals such as apatite (Li et al. 2007) entails relatively minor absolute differences in rhizosphere pH, and therefore may be outstripped by the greater root biomass of maize. Additionally, differences in rhizosphere acidification between maize and soybean change over time, with initially greater rhizosphere acidity for soybean under P deficiency than maize but the opposite occurring after approximately two weeks (Zhou et al. 2009).

Maize plant height at V12 at the field scale has been found to be strongly correlated with yield ($r^2 = 0.87$) (Yin et al. 2011). In the current experiment, the inverse relationship of maize biomass to the proportion of struvite suggests the possibility of yield losses with extensive or complete substitution of MAP with struvite. The two studies to-date that assess grain yields under struvite fertilization have found similar maize, soybean, and wheat yields compared to triple superphosphate across a wide range of P application rates (Talboys et al. 2016; Thompson et al. 2013). In the present study, vegetative biomass indicates that only a proportion of P inputs can be substituted with struvite (up to 50% in maize and 25% in soybean), supporting the hypothesized necessity of a highly water soluble P source for early growth. This ratio may be specific to MAP, because dissolution of DAP does not yield a net increase in soil solution H^+ that would favor struvite dissolution. Blending struvite with DAP instead of MAP could therefore potentially lower the proportion of struvite tolerated by maize and soybean in vegetative growth stages. Placement would likely affect the proximity of H^+ generated by MAP dissolution to struvite granules, since broadcast is unlikely to co-locate MAP and struvite granules. Banding or co-granulation of struvite: MAP blends is likely to maximize this potential interaction, though the minor to non-significant effect of banding in our study suggests an overall limited magnitude of this solubilization mechanism.

Biomass P and N nutrient concentrations were diluted by greater biomass growth resulting in total nutrient uptake that did not correspond to fertilizer treatment specific dry matter accumulation, contrary to the expectation there would be more significant differences in P uptake. One possible explanation is that early-season P deficiency, previously observed for wheat fertilized with struvite (Talboys et al. 2016), occurred due to lower dissolution rates under a smaller root biomass. Since early stage (pre-V6) P deficiency in maize can constrain subsequent growth even after P deficiency is alleviated (Grant et al. 2001), early stage P deficiency with a greater proportion of struvite may have entrenched a growth penalty even when P supply increased later on as root biomass was sufficient to drive solubilization. Higher crop P concentrations have been linked to greater nutrient availability as well as – seemingly paradoxically – P deficiency (Jarrell and Beverly 1981). Dilution of biomass P concentrations with increasing biomass has been observed previously across P availability

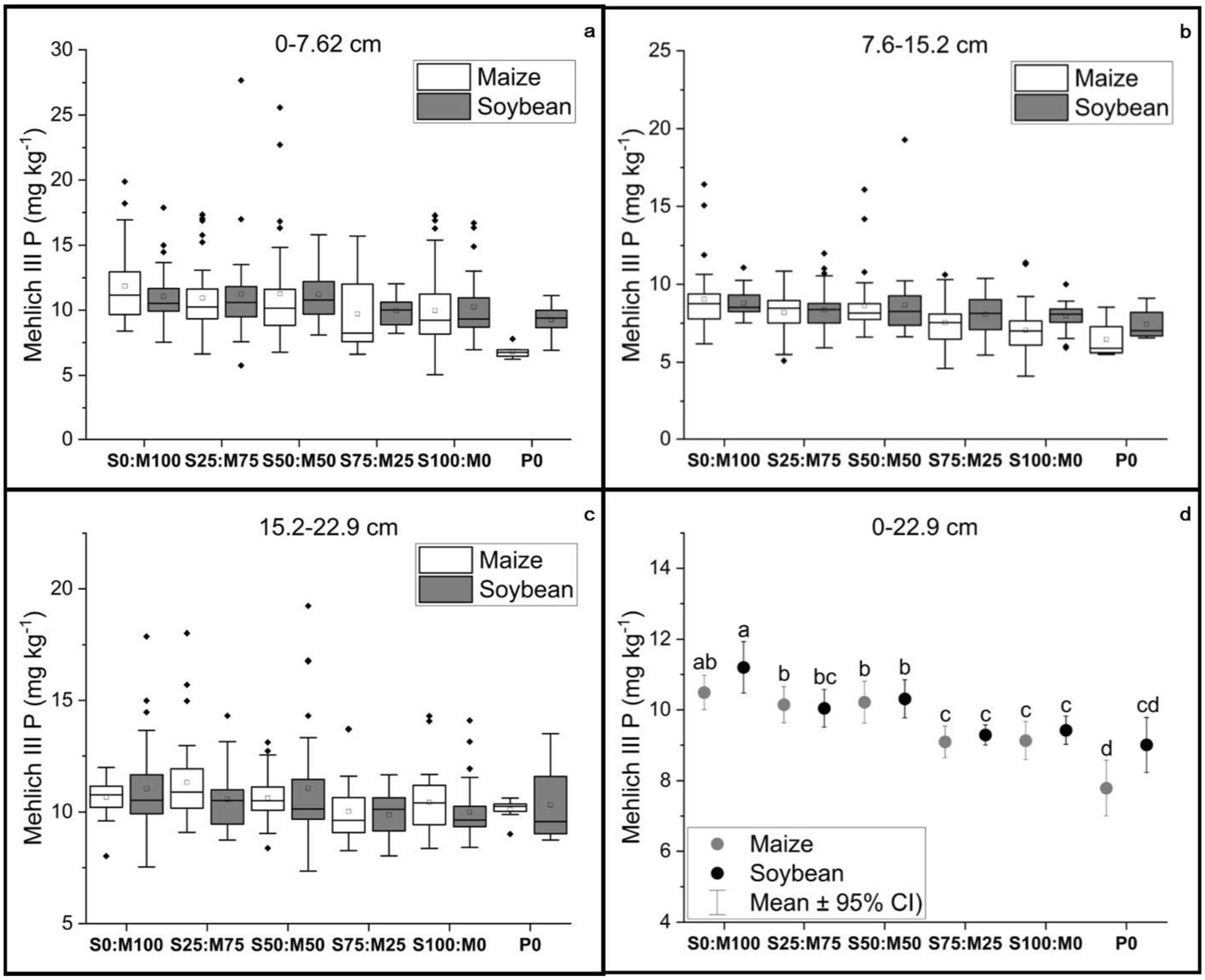

Fig. 3 Soil Mehlich-3 P concentration (**a**) at 0–7.6 cm (**b**), at 7.6–15.2 cm, and (**c**) at 15.2–22.8 cm, and (**d**) averaged across all measured depths in soils used to grow maize and soybean using struvite (S), monoammonium phosphate (M), and S: M blends, as well as a P-unfertilized control (P0). Means with the same letter are not significantly different at $\alpha = 0.05$

Table 5 Type III fixed effects describing struvite granule size influence on soil Mehlich-3 P concentrations in soils used to grow maize and soybean. Analysis excludes the MAP treatment (S0:M100) and the P-unfertilized control (P0), as neither contained struvite

	df	Sum squares	Mean square	F value	Pr(>F)
Maize					
Treatment (Does not include S0:M100, P0)	3	108	36.01	5.68	<0.001***
Granule size	1	26.9	26.93	4.248	0.04**
Treatment:Granule	3	125.5	41.83	6.599	<0.001***
Residuals	370	2345.6	6.34		
Soybean					
Treatment (Does not include S0:M100, P0)	3	63	21.013	4.303	0.00535**
Granule size	1	7.5	7.531	1.542	0.21512
Treatment:Granule	3	61.2	20.409	4.18	0.00632**
Residuals	345	1684.6	4.883		

Table 6 Mean ammonium (NH_4^+) and nitrate (NO_3^-) N concentrations at 0–7.6 cm, 7.6–15.2 cm, 15.2–22.8 cm, and averaged across all three depths for struvite (S), monoammonium phosphate (M), and S: M blends, as well as a P-unfertilized control (P0)

	0–7.6 cm		7.6–15.2 cm		15.2–22.8 cm		Mean	
Treatment	NH_4^+-N	NO_3^--N	NH_4^+-N	NO_3^--N	NH_4^+-N	NO_3^--N	NH_4^+-N	NO_3^--N
	mg kg^{-1}							
Maize								
S0:M100	5.0	28.4	11.4	32.1	11.5	49.1	9.3	36.6
S25:M75	4.7	23.0	11.7	30.3	11.1	47.9	9.2	33.7
S50:M50	5.2	27.2	13.2	26.9	11.3	49.1	9.9	34.4
S75:M25	5.5	29.0	13.2	24.5	11.7	44.9	10.1	31.3
S100:M0	5.5	36.6	12.0	37.1	11.6	59.6	9.7	44.4
P0	4.9	35.2	12.2	92.7	10.9	97.6	9.3	75.1
Soybean								
S0:M100	5.2	39.1	6.5	36.0	5.6	45.3	5.7	40.1
S25:M75	5.4	37.6	6.0	35.0	4.8	48.0	5.4	40.2
S50:M50	5.0	40.3	4.6	35.8	4.4	40.8	4.6	39.0
S75:M25	5.2	47.8	4.8	36.8	4.3	40.3	4.8	41.7
S100:M0	5.2	37.8	5.9	36.2	4.4	39.2	5.2	37.7
P0	4.8	42.5	4.9	44.9	4.4	56.0	4.7	47.8

gradients. For maize, Terman et al. (1975) demonstrated that shoot P concentrations decreased markedly with increasing biomass driven by increasing P application rates. This is consistent with other plants exhibiting what has been interpreted as P dilution due to the accumulation of new biomass from faster growth rates (Williams 1948; Zhang et al. 2019), also known as the Piper-Steenbjerg effect (Wilkstrom 1994). Similarly, Fox (1978) observed that under P-deficient conditions in greenhouse and field settings, P applicant gradients entailed greater shoot biomass as a result of lower P concentration, which was also interpreted a growth dilution effect. That vegetative stage plant P concentrations were inverse to biomass in this experiment highlights the need to report total biomass P in order to identify differences in crop P uptake. These results also highlight the importance of belowground measurements of plant biomass and uptake. Minor differences in maize P and N uptake measured among P fertilizer treatments and the absence of the same in soybean would not have been identified without belowground measurements, as aboveground values were similar across treatments for both crops.

Soybean may not have responded to P fertilization because P and N uptake were similar between fertilized and unfertilized soybean. Uptake of P and N was greater for fertilized maize despite the lower concentrations than the higher P and N concentration but lower biomass of P-unfertilized plants, suggesting an aboveground biomass dilution effect. Plant biomass dilution of a nutrient occurs when the rate of dry matter accumulation exceeds the rate of nutrient uptake (Jarrell and Beverly 1981). Additionally, greater biomass nutrient concentrations in unfertilized control plants relative to fertilized plants have been attributed to acute nutrient stress, limiting the potential of a growth response even when eventually accumulating adequate nutrient concentrations (Hiatt and Massey 1958). Though there was no difference in maize P uptake across MAP and struvite: MAP fertilized treatments at the time of harvest, significant biomass differences that may have been incurred from earlier acute P stress. Maize fertilized with struvite alone had significantly less total P uptake than maize fertilized with only MAP, indicating that full substation of MAP by struvite is insufficient to meet early season crop P needs (Talboys et al. 2016; Margenot et al. 2019).

The P limitation thought to have inhibited maize growth had a strong effect on N uptake despite having received excess N. Total N uptake of maize closely matched that of total P uptake. Soybean total P uptake in plants fertilized with the 25 and 50% struvite blends took up less P (8%) than plants fertilized with struvite alone, contrary to our hypothesis, but AFPU was similar across struvite: MAP treatments. As has been documented for the same soil type used in this experiment, by the V12 stage maize takes up approximately 27% of the total P at maturity and by the R1 stage soybean has taken up 30% (Bender et al. 2012, 2015). At a similar percentage of total P uptake, maize plants grown in the present experiment took up 3-fold more P than soybean (120 mg vs 40 mg) and accumulated more than triple the total biomass.

Apparent fertilizer P uptake and APUE are limited by the inability to track the fate of P derived from fertilizers. Exact measurements of fertilizer P uptake are not possible without isotopically labeling P (i.e., ^{32}P or ^{33}P). Apparent P use efficiencies were expected to be low because the P application rates used were based on grain removal plus soil P buildup, yet both crop species were grown to the end of vegetative stage and thus had taken up less than one-third of total P uptake at the time of biomass harvest. Nonetheless, a significant fertilizer treatment effect on P uptake was observed for V12 maize but not R1 soybean. Apparent P use efficiencies for maize were 9–14%, in agreement with apparent P fertilizer recoveries of 10–15% (Johnston et al. 2014). Phosphorus use efficiencies obtained from ^{32}P-labeled fertilizer generally do not exceed 25% (Johnston et al. 2014). The increase of AFPU and APUE with decreasing proportions of struvite indicates early growth stage maize requires P fertilization and that maize cannot reach full vegetative growth potential with struvite alone, suggesting a yield penalty for maize fertilized with only struvite in P-responsive soils (19 mg kg^{-1} Mehlich-3). This finding is contrary to greenhouse studies reporting similar, if not significantly greater, crop biomass and P uptake response to full substitution of highly water soluble P fertilizers with struvite, suggesting those results may be confounded by low soil masses, high soil test P, and excessive struvite application rates (Hertzberger et al. 2020). Across 59 studies analyzed by Hertzberger et al. (2020), there were only 15 paired aboveground biomass observations where struvite was compared to ammonium phosphates or superphosphates. On average, aboveground biomass was 6% lower when fertilized with struvite (Hertzberger et al. 2020), whereas in the present study aboveground maize biomass was 19% and soybean aboveground biomass was 22% lower when MAP was fully substituted by struvite.

Soil mass used in greenhouse experiments determines the total amount of soil P available to plants as well as root density. Low soil masses may overestimate struvite performance through increased plant reliance on fertilizer inputs and may underestimate performance due to densely packed roots and extensive mining of soil P. Soils used for this experiment (14 kg) were, by visual observation, well explored by the roots of V12 maize grown for 45 days. In contrast, past greenhouse struvite studies have used a range of 1–15 kg soil ($n = 68$) to grow maize and an experimental duration of 28–135 days ($n = 68$) (Hertzberger et al. 2020). Likewise, employing soils with high plant-available P could overestimate plant growth response due to an abundance of non-struvite P already in the soil. Ten percent ($n = 66$) of field scale paired struvite-ammonium phosphate or super phosphate observations and 29% ($n = 113$) of greenhouse observations were conducted in soils with high soil test P (Hertzberger et al. 2020). Excessive struvite application rates may favor plant growth response to struvite by providing adequate P despite struvite's low water solubility. Hertzberger et al. (2020) revealed that 50% (n = 66) of field scale paired struvite-ammonium phosphate or super phosphate observations and 73% (n = 113) of greenhouse scale observations used excessive P application rates (i.e., well above recommended practices for build-and-maintain). In some instances, struvite was finely ground, leading to more rapid solubilization and increasing struvite-P availability to plants.

Soil test P and N

The use of a soil with slight P deficiency and realistic field-scale P fertilization rates enabled testing of hypothesized effects of fertilizer blend and struvite granule size on soil test P. Initial soil Mehlich-3 P (colorimetric) concentration was lower than the concentration considered optimal for maize and soybean growth in north-central Illinois (20–25 mg kg^{-1}) and an increase in Mehlich-3 P was expected with increasing degree of struvite substitution for MAP. Unexpectedly, soil Mehlich-3 P concentrations after plant harvest were 41–58% lower than the original 19 mg kg^{-1} for all treatments and both crops. Despite the overall mining of Mehlich-3 P, this extractable P fraction increased with greater proportions of MAP as hypothesized, consistent with the order of magnitude greater water solubility of MAP (22%) compared to struvite (2–3%) (Maluf et al. 2018; Rech et al. 2019; Gu et al. 2020).

However, struvite and MAP may exhibit similar solubility in the presence of organic acids. The commercial struvite used in this study (Crystal Green™) has been found to be 29.1% soluble in citric acid and 28.8% soluble in neutral ammonium citrate + water (NAC + H_2O). This is overall similar to MAP, which is 22.5% soluble in citric acid and 23.5% soluble in NAC + H_2O (Maluf et al. 2018; Rech et al. 2019). Citric acid and NAC + H_2O solubilities (30 min extraction) as high as 100% have been reported for struvite precipitated from digested sewage sludge (> 0.05 mm) but those struvites included Ca, K, and heavy metal impurities that could alter solubility (Kern et al. 2008).

Mean Mehlich-3 P concentrations were higher in soils fertilized with 50% or more MAP. Struvite granule size did not have as strong an effect on soil Mehlich-3 P concentrations as the ratio of struvite to MAP, highlighting the greater relative importance of the degree of struvite substitution than struvite granule size. The effect of struvite granule size was significant for maize but not soybean likely because of the greater difference in maize P uptake across the struvite substitution gradient, heightening changes in soil extractable P relative to soybean. Degryse et al. (2017) found greater struvite dissolution and soil P diffusion when struvite was ground into a powder (< 0.15 mm) over granular form, supporting the higher Mehlich-3 P concentrations from 1.5 mm struvite over 3.0 diameter granules in our study. Across 59 studies, struvite granule sizes in the range of 0.75 to 2.4 mm diameter were not evaluated. The present study identifies that struvite granules in this overlooked size range (1.5 mm diameter) may produce distinct effects on soil test P, though not necessarily crop growth, compared to larger granules. Caution was taken to exclude residual struvite granules in the soils used for Mehlich-3 extraction, as this and other common soil test extractants may dissolve struvite and artificially increase extractable P concentrations.

Because maize was fertilized with relatively high rates of N largely as ammonium and urea (UAN), extractable NH_4^+-N concentrations were higher for soils used to growth maize than soybean (Table 6). Soil NO_3^--N concentrations for maize fertilized with 0–75% struvite were lower than in soil used for soybean regardless of treatment. Lower soil NO_3^--N concentrations may have resulted from the greater maize biomass and thus N uptake in all P fertilizer treatments excluding 100% struvite. Soil NO_3^--N concentrations also increased with depth in soils used to grow maize, indicating downward movement of fertilizer and/or mineralized N from nearly-daily watering. Soil NO_3^--N concentrations were greatest in soils used to grow maize fertilized with 100% struvite or not P-fertilized, likely because of the significantly lower fertilizer N uptake.

Environmental implications

Lower soil test P (Mehlich-3 extractable) after plant removal at greater proportions of struvite in blends support the hypothesized potential of struvite to reduce dissolved P loss risk. This is consistent with the approximately 10-fold lower water solubility of struvite compared to MAP. Soil Mehlich-3 P concentrations were higher for 1.5 mm versus 3.0 mm diameter struvite granules, supporting the hypothesis of greater solubilization of smaller diameter struvite. Placement did not influence soil Mehlich-3 P concentrations, but this may not translate to the field-scale where banding P directly in the root zone can limit surface run-off P loss risk compared to incorporated broadcasted P applications. Banding P fertilizer during planting further avoids the loss risk of fall-applied P (Grant and Flaten 2019). A significant positive correlation ($r^2 = 0.90$) between surface runoff P concentrations and soil Mehlich-3 P concentrations has been documented (Sharpley 1995), suggesting greater P loss risk in soils with higher Mehlich-3 P concentrations. Although soil Mehlich-3 P concentrations have been found to be positively related to dissolved P concentrations in runoff, a concentration threshold of >50 mg kg^{-1} appears to risk high surface run-off losses (Sharpley 1995). This study demonstrates that blends of ≤50% struvite with MAP have the potential to lower P loss risk over 100% MAP applications while maximizing crop growth potential.

Conclusions

To mitigate impairment of surface water quality by P losses from non-point agricultural sources, struvite has hypothesized potential as a P fertilizer with lower P loss risk. Struvite:MAP blends were evaluated for their ability to maximize early season growth of maize and soybean while lowering P loss risk (soil Mehlich-3 P). As hypothesized, struvite alone was unable to maintain early season (i.e., vegetative) crop growth, but blends of struvite with highly water soluble MAP support similar biomass and P uptake as MAP only. Maize and soybean biomass decreased with increasing struvite proportions in struvite: MAP blends. Maize biomass was similar with up to 50% substitution of MAP by struvite and up to 25% substitution for soybean. Uptake of P in maize was more pronounced than in soybean and inversely correlated with the proportion of struvite. Lower post-harvest soil Mehlich-3 P concentrations with increasing proportions of struvite supported the hypothesized benefit of struvite: MAP blends to decrease P loss risk. Regardless of crop species, soil Mehlich-3 P concentrations were 14% higher on average for blends with up to 50% struvite. A minor but significant decrease (5%) in soil Mehlich-3 P concentrations for smaller struvite granules (1.5 vs 3.0 mm diameter) indicates that granule size effects on hypothesized soil P loss risk are secondary to the degree of struvite substitution for MAP. Struvite granule size and placement did not influence crop growth responses, and placement did not impact soil Mehlich-3 P concentrations. Results indicate that depending on the crop species, substituting struvite for MAP by up to 25–50% (on a P basis) can still meet crop P demand while lowering soil Mehlich-3 P and thus P loss risk.

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