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Relative Agronomic Effectiveness of Struvite Phosphorus for Perennial Ryegrass (*Lolium perenne*) in Contrasting Grassland Soils

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Correspondence: Florenzia DeLucca-Agreló (flor.deluccaagreló@lincolnuni.ac.nz)**Received:** 18 March 2026 | **Revised:** 27 May 2026 | **Accepted:** 29 May 2026**Keywords:** fertilizer | *lolium perenne* L. | phosphorus retention capacity | phosphorus use efficiency | single superphosphate

ABSTRACT

New Zealand grassland systems rely heavily on imported phosphorus (P), yet conventional water-soluble fertilizers such as single superphosphate are used inefficiently and contribute to legacy P accumulation and water quality risks. Recovered P from wastewater, such as sparingly soluble struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$), offers a potentially more sustainable alternative. This study evaluated the agronomic effectiveness of struvite compared with superphosphate in two acidic grassland soils with contrasting P retention capacities (12% and 96%). Perennial ryegrass (*Lolium perenne* L.) was grown for 3 months under controlled conditions. Treatments included two P sources (struvite and superphosphate) applied at 0, 15, 30, and 60 mg P kg⁻¹. Measurements included dry matter yield, plant P uptake, relative agronomic effectiveness, and residual soil Olsen-P. Fertilizer application significantly increased plant growth and P uptake. While dry matter yields were similar between fertilizers, struvite increased plant P uptake by 49% compared with superphosphate across soils and rates. Relative agronomic effectiveness of struvite was greater in the low P retention soil. Olsen-P concentrations were consistently higher under struvite in both soils. These results indicate that struvite is a viable alternative to superphosphate in acidic grassland soils, particularly in those where high P-retention limits P availability.

1 | Introduction

Phosphorus (P) input in the form of mineral fertilizer is fundamental to maintaining the productivity of grassland farming systems in New Zealand, which generate over half of the country's export income (Caradus et al. 2023; Rys et al. 2021). Phosphorus fertilizers are applied primarily to enhance the growth of both grasses (e.g., perennial ryegrass—*Lolium perenne* L.) and legumes (e.g., white clover—*Trifolium repens* L.), with legumes additionally promoting biological N fixation through symbiosis with rhizobia, thereby improving soil N status and increasing overall pasture productivity (Roberts and Withe 2016). Most grassland soils in New Zealand are acidic (<pH6), and currently ~150,000 tons of P are applied per annum mainly as single superphosphate (SSP) manufactured

from imported phosphate rock (Fertiliser Association of New Zealand 2025; Smith et al. 2012).

While SSP is a highly water-soluble source that supplies readily plant-available P, much of the added P becomes unavailable due to sorption, precipitation, and binding with organic matter (Wang et al. 2023). As a result, substantial fertilizer inputs are required to sustain soil P concentrations at levels adequate for optimal plant growth, yet crops effectively take up less than 25% of the applied P (Roberts and Johnston 2015). Repeated P inputs over time have therefore resulted in the accumulation of residual, plant-unavailable P in soils (i.e., legacy P) (Gatiboni et al. 2020). This accumulated soil P can be lost through leaching or surface runoff, which can contribute to increasing P in water

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bodies and accelerating eutrophication (De Lucca Agrelo et al. 2025).

Concerns regarding the limited availability and uneven global distribution of phosphate rock reserves, together with the low use efficiency of conventional mineral P fertilizers and the degradation of aquatic systems, have intensified interest in improving the sustainability of agricultural P management. In response, there is growing interest in closing the P cycle through the recovery and reuse of P from waste materials (Michael et al. 2023; Raniro et al. 2025). Among these, the recovery of sparingly soluble struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) recovered from municipal and industrial wastewater has emerged as a promising alternative to conventional water-soluble phosphate fertilizers derived from phosphate rock (Cabeza et al. 2011; Schneider et al. 2019). In New Zealand, struvite is currently recovered from municipal wastewater by Watercare (Auckland), with future production capacity projected to reach approximately 3,000 tons per year (Sustainable Business Network 2023). Struvite is considered a slow-release fertilizer due to its low water solubility (<5%), which enables a more gradual and sustained supply of P to plants, potentially improving P uptake efficiency and reducing losses to the environment (Morrison et al. 2023).

New Zealand grassland soils are characterized by predominantly acidic conditions ($\text{pH} < 6.0$) and medium to high P retention capacities (30–84%) (Morton et al. 2003; Scrimgeour 2016). Under these conditions, fertilizer P management is particularly challenging, as much of the applied P is rapidly retained through sorption onto iron and aluminum hydroxides (Nash et al. 2020). It has been suggested that the slow-release characteristics of struvite may be advantageous in soils with high P retention capacity, as gradual dissolution may better match plant P demand, reduce sorption losses, and enhance overall P use efficiency (Peeva et al. 2021).

Although the agronomic performance of struvite relative to conventional soluble fertilizers has been widely investigated, most studies have focused on arable cropping systems and neutral to alkaline soils ($\text{pH} > 7$) (Hertzberger et al. 2020). Consequently, its performance in acidic grassland soils and the specific role of soil P retention in controlling struvite agronomic effectiveness remain poorly understood, and limited research has been conducted on the potential of struvite as a P fertilizer under New Zealand soils and climatic conditions (DeLucca-Agrelo et al. 2026).

The main objective of this study was to investigate and quantify the relative agronomic performance of struvite and SSP in ryegrass, as influenced by soil properties that determine the reactions and fate of fertilizer P, principally P retention capacity. It was hypothesized that the agronomic performance of P applied as struvite would be equal to or greater than that of SSP and that soil P retention capacity adversely impacts the plant availability of both P sources to a different extent.

2 | Methods

2.1 | Soils

Two grassland soils with contrasting P retention capacities and low levels of plant-available P were selected for this study.

A silt loam soil with low P retention capacity (New Zealand classification: Pallic Grey Earth; USDA classification: Fragiudalf) collected from Otago (latitude $44^\circ 38' 01.93'' \text{S}$, longitude $169^\circ 19' 42.89'' \text{E}$; designated as Mt Grand soil) and a sandy loam soil (New Zealand classification: Typic Orthic-Allophanic; USDA classification: Typic hapludand) obtained from Taranaki (latitude $39^\circ 45' 24.2'' \text{S}$, longitude $174^\circ 04' 24'' \text{E}$; designated as Taranaki soil). The high P retention of the Taranaki soil is attributed to its mineralogy consisting of allophane materials, aluminosilicates derived from volcanic ash, with a large specific surface area and abundant reactive sites that strongly adsorb P (Ballantine and Tanner 2010). The soils were air-dried and sieved to <4 mm. Before the commencement of the experiment, a subsample of each soil (<2 mm) was analyzed for pH (1:2 soil-to-deionized water ratio) (Blakemore et al. 1981), exchangeable cations (K, Ca, Mg, and Na) (Schollenberger and Simon 1945), Olsen-P (1:20 soil-to-extractant ratio) (Olsen et al. 1954), organic carbon (C) and total nitrogen (N) (Dumas combustion), total P (USEPA 1996), P retention capacity (assessed by shaking the soil with a solution containing 1000 mg P L^{-1} at pH 4.6 for 16 h) (Saunders 1965), and soil texture (Miller and Miller 1987) (Table 1).

2.2 | Phosphorus Sources

The P fertilizers used in this study were a commercial struvite (Emerge) derived from urban wastewater produced by Watercare Auckland (12.3% total P, 99% citric-soluble, 4% water-soluble, 5% N, 10% Mg) and SSP produced by Ballance Agri-nutrients (12% total P, 85% citric-soluble, 84% water-soluble, 11% S). To homogenize particle size, fertilizers were ground (<0.2 mm) prior to use in the experiment.

2.3 | Experimental Setup

A pot experiment was carried out in a controlled environment glasshouse between March and June 2024 (temperature 10°C – 28°C). The experiment consisted of a randomized block design with four replicates combining soil type (Mt Grand, Taranaki), P source (struvite, SSP), and P rate (15, 30, and 60 mg P kg^{-1}),

TABLE 1 | Initial chemical and physical properties of the soils used in the study.

Property	Mt Grand	Taranaki
Texture	Silt loam	Sandy loam
pH (water)	5.6	5.7
Organic C	5.6	2.5
Total N	0.48	0.26
Rel C/N	11.6	9.7
CEC cmol kg^{-1}	15	11
TP mg kg^{-1}	582	1554
Olsen-P mg kg^{-1}	12	11
P retention capacity (%)	12	96

Abbreviations: CEC, cation exchange capacity; TP, Total P.

while a control treatment without P addition (0P) was included for each soil.

Prior to commencing the experiment, struvite and SSP were thoroughly mixed with the soils at rates equivalent to 15, 30, and 60 mg P kg⁻¹ (designated as 15P, 30P, and 60P), corresponding to 18, 36, and 72 kg P ha⁻¹, and placed into 1 L square plastic pots (9 × 9 × 20 cm), assuming a bulk density of 1.2 and 0.9 g cm³ for Mt Grand and Taranaki, respectively. Before seeding the pots, fertilizer N (urea, 46% N) and sulfur (S) (CaSO₄·2H₂O, 18.6% S) were applied to match the content of the highest rate of struvite for N and SSP for S, and potassium (KCl, 50% K) was also added to all the pots at a rate of 50 mg kg⁻¹ (Table S1).

Perennial ryegrass was then sown at a target plant population of five plants pot⁻¹. The pots were irrigated daily using an automatic irrigation system with soil moisture sensors to keep the soil moisture at 70% of the water-holding capacity. The experiment was conducted for 3 months. Ryegrass shoots were harvested from the same pots at 30, 61, and 90 days after sowing, when plants reached a height of 15–20 cm. Nitrogen was reapplied (as urea) after each harvest at a rate equivalent to 50 mg N kg⁻¹.

Freshly harvested shoot samples were oven-dried at 60°C for 72 h, and dry weight was recorded for dry matter (DM) yield determination. Finely ground (<0.15 mm) dry samples were analyzed for total P concentration by muffle combustion at 500°C, followed by HCl digestion and colorimetric P content determination (Murphy and Riley 1962).

At the end of the experiment, roots were carefully removed, and soils were dried at 40°C for 72 h and sieved (<2 mm) prior to determination of Olsen-P.

2.4 | Calculations

Accumulated DM yield (g pot⁻¹) was the total DM summed across the three harvests. Shoot P uptake (mg P pot⁻¹) was calculated using Equation (1), and cumulative P uptake was determined by accumulating the three harvests. The relative agronomic effectiveness (RAE) (%) of struvite was calculated using Equation (2).

Shoot P uptake (mg P pot⁻¹) =

[DM yield × P concentration in plant]

(1)

RAE struvite (%) = $\frac{P_{\text{uptake struvite}} - P_{\text{uptake control}}}{P_{\text{uptake SSP}} - P_{\text{uptake control}}}$

(2)

2.5 | Statistical Analysis

All the analyses were conducted in R Core Team (2023) using “dplyr” for data processing. An analysis of variance (ANOVA) was performed to determine the effect of fertilizer type (i.e., struvite, SSP), P rate (treated as a factor; 0, 15, 30, and 60 mg P kg⁻¹), and soil type (i.e., Mt Grand, Taranaki), and their interactions on the accumulated DM yield of ryegrass, the shoot P uptake, agronomic effectiveness of struvite, and soil Olsen-P. Pairwise comparisons were performed using Tukey’s honestly significant difference (HSD) test at P < 0.05 level of significance from the “agricolae” package. Homogeneity of the variance and normal distribution of the residuals was determined by visual assessment of residual plots and the Shapiro–Wilk test.

3 | Results

3.1 | Plant Dry Matter Yield

Overall, mean ryegrass DM yield was 4.70 g pot⁻¹ and ranged from 1.31 to 6.94 g pot⁻¹, across all fertilizers, application rates, and soil types. Cumulative ryegrass yield was significantly affected by fertilizer type, P rate, and soil type (Table 2). There was a response in plant DM yield to P fertilization. Phosphorus fertilization significantly increased ryegrass yield (P < 0.001); on average, fertilized treatments yielded more than the control treatment (5.1 g DM pot⁻¹ vs. 2.6 g DM pot⁻¹). Struvite resulted in similar ryegrass yield to SSP (4.3 and 4.6 g pot⁻¹, respectively). Increasing P application rates resulted in progressively higher (P < 0.001) DM yields, with the greatest yields observed at the 60P rate (6.2 g pot⁻¹; Figure 1). Soil type also influenced biomass production; ryegrass produced significantly more DM in Mt Grand soil than in Taranaki (4.9 vs. 4.1 g pot⁻¹; P < 0.001). The interaction of P fertilizer x rate also

TABLE 2 | p-values for the effects of fertilizer type (P; struvite, SSP), P rate (R; 0, 15, 30, 60), soil (S; Mt Grand, Taranaki), and their interactions on shoot DM yield (g pot⁻¹), shoot P concentration (%), P uptake (mg P pot⁻¹), and Olsen-P (mg P kg⁻¹ soil).

Effect	Shoot DM yield	Shoot P %	P uptake	Olsen-P
P	ns	***	***	***
R	***	***	***	***
S	***	***	***	***
P × R	**	**	*	***
P × S	ns	***	***	ns
S × R	***	ns	*	ns
P × R × S	ns	ns	ns	*

Note: ns = not significant (P > 0.05);

* p < 0.05;

** p < 0.01;

*** p < 0.001.

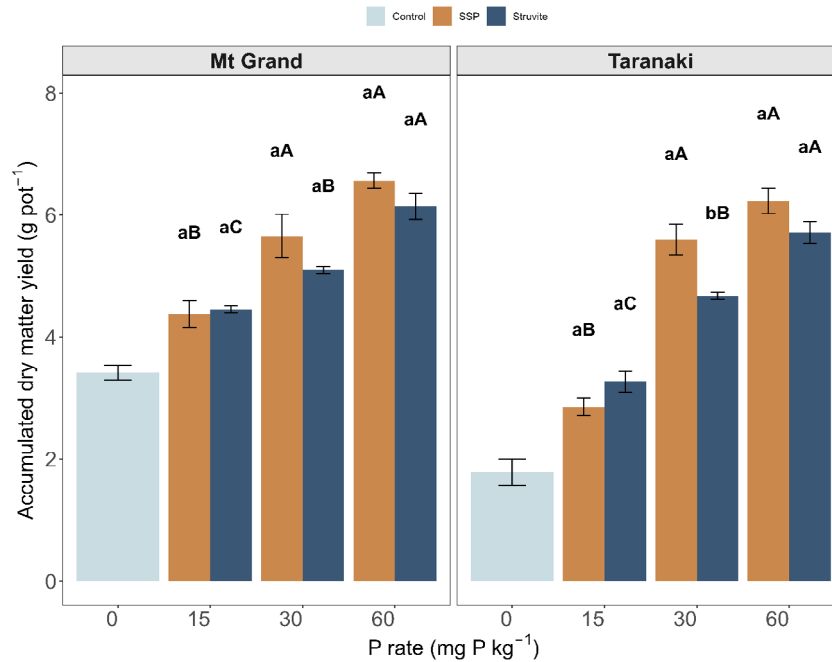


FIGURE 1 | Accumulated shoot dry matter yield (g pot^{-1}) of ryegrass in response to P fertilizer (struvite, SSP) and applied P rate (0, 15, 30, and 60 mg P kg^{-1}) in two soils (Mt Grand, Taranaki). Different lowercase letters denote significant differences between P sources within each P rate, and different uppercase letters indicate significant differences between P rates within each fertilizer (Tukey, $P < 0.05$). Comparisons are made only between fertilizer treatments, excluding the control.

significantly affected ryegrass cumulative DM yield (Table 2). At the 60P rate, both struvite and SSP yielded the highest biomass (5.9 and 6.4 g pot^{-1} , respectively), averaged across soils. The lowest yields were obtained with SSP and struvite applied at a rate of 15P (3.6 and 2.9 g pot^{-1} , respectively).

Ryegrass DM yield was significantly affected by the interaction between P rate $\times$ soil type (Table 2). Yield increased with increasing P rate in both soils, with significant differences among all P rates within each soil ($P < 0.001$). A stronger response to P fertilization was observed in Taranaki compared with Mt Grand (Figure 1). In Mt Grand soil, yield increased from 4.42 to 5.38 and 6.35 g pot^{-1} at 15, 30, and 60 kg P ha^{-1} , respectively, representing increases of 22% from 15 to 30 kg P ha^{-1} and 18% from 30 to 60 kg P ha^{-1} (44% overall increase from 15 to 60 kg P ha^{-1}). In Taranaki soil, responses to P were more pronounced, with yield increasing from 3.06 to 5.14 and 5.97 g pot^{-1} across the same P rates. This corresponds to a 68% increase from 15 to 30 kg P ha^{-1} and a further 16% increase from 30 to 60 kg P ha^{-1} , resulting in a 95% overall increase across all P rates.

3.2 | Shoot Phosphorus Concentration and Phosphorus Uptake

Phosphorus fertilization had a significant effect on shoot P concentration ($P < 0.001$). Relative to the control, struvite resulted in a 2.46-fold increase in shoot P concentration, whereas SSP produced a 1.69-fold increase (Figure 2). Across all P rates and soils, P concentration was significantly higher under struvite than SSP (0.48% vs. 0.32% , respectively; $P < 0.001$; Table 2), and it also

increased ($P < 0.001$) with increasing P rates. Soil type also had a significant effect ($P < 0.001$) on shoot P concentration, with greater values observed in Mt Grand (0.47%) than in Taranaki (0.27%).

Significant interactions were also observed between fertilizer type $\times$ rate ($P < 0.01$). Within each P rate, shoot P concentration was consistently higher ($P < 0.001$) under struvite than SSP; at 15P, struvite shoot P concentration was 0.40% , while for SSP it was 0.31% . The magnitude of the difference increased at higher P application rates; at 30P, shoot P concentration was 0.51% under struvite compared with 0.32% under SSP, while at 60P, values increased to 0.53% and 0.33% , respectively.

The fertilizer type $\times$ soil type interaction also significantly ($P < 0.001$) affected the shoot P concentration. In Mt Grand, struvite resulted in higher ($P < 0.001$) P concentration values than SSP (0.62% and 0.41% , respectively). A similar pattern was observed in Taranaki soil, although responses were smaller. Struvite also showed higher ($P < 0.001$) shoot P concentration than SSP (0.35% and 0.23% , respectively).

Ryegrass P uptake increased significantly ($P < 0.001$) with P application rate and differed between fertilizer types (Table 2, Figure 3). Across P rates and soil types, struvite led to a greater ($P < 0.001$) P uptake than SSP in ryegrass (18.8 vs. $14.6 \text{ mg P pot}^{-1}$), which represented a 22% increase over SSP.

The highest ($P < 0.001$) P uptake was observed at 60P ($26.5 \text{ mg P pot}^{-1}$). Compared to the control, a 2.7-fold increase in P uptake was observed at the 15P rate. Doubling the P rate from 15P to 30P resulted in a further 1.4-fold increase in plant

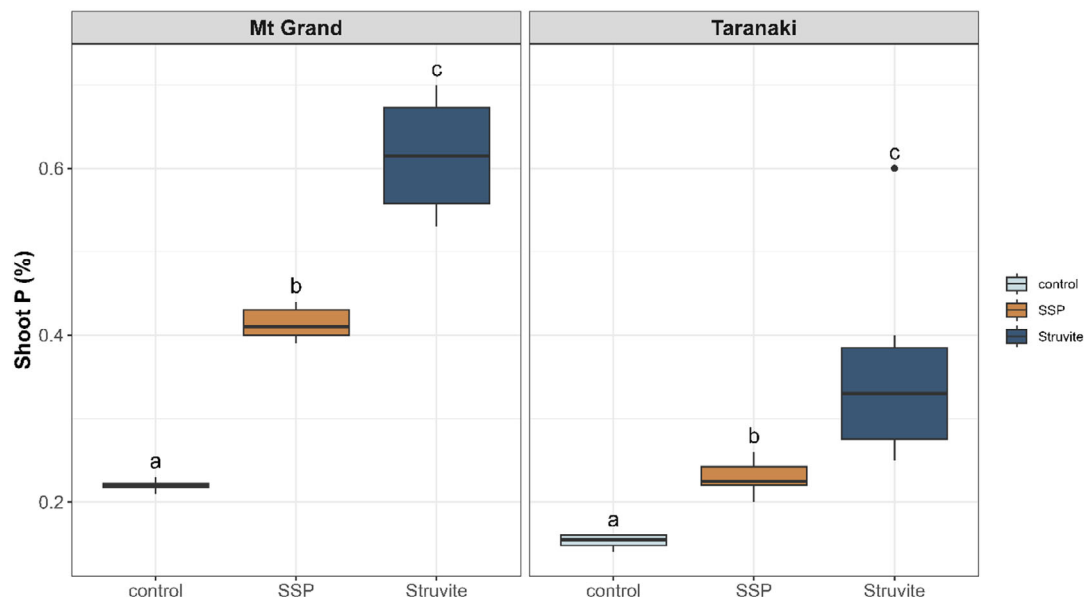


FIGURE 2 | Effect of phosphorus (P) fertilization treatments on shoot P concentration (%) in two soils (Mt Grand and Taranaki). Within each soil type, treatments sharing different letters are significantly different according to Tukey's test ($P < 0.05$).

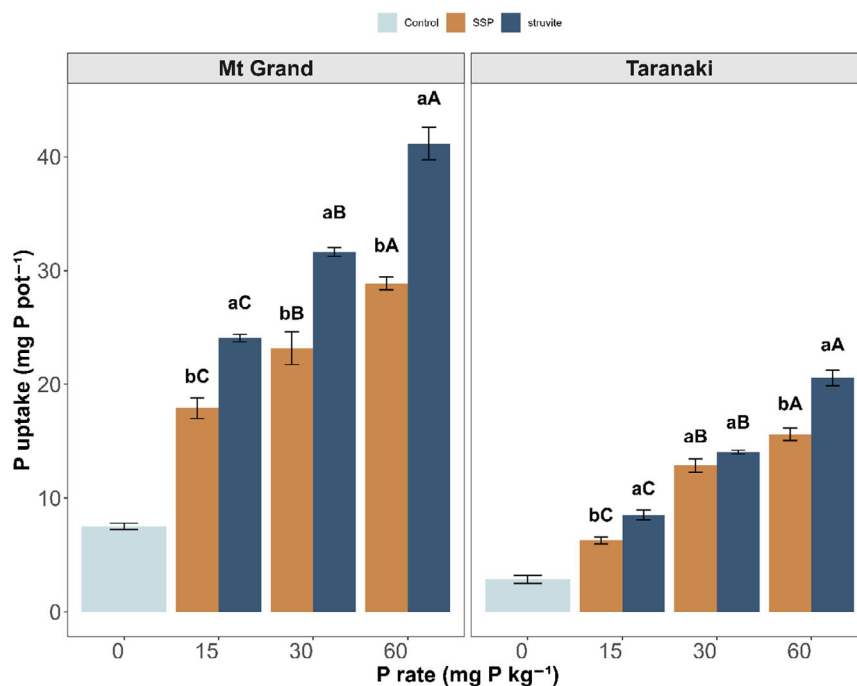


FIGURE 3 | Total P uptake (mg P pot^{-1}) by ryegrass determined in response to P fertilizer (struvite, SSP) and P application rate (0, 15, 30, and 60 mg P kg^{-1}) in two soils (Mt Grand and Taranaki). Different lowercase letters denote significant differences between P sources within each P rate, and different uppercase letters indicate significant differences between P rates within each fertilizer (Tukey, $P < 0.05$). Comparisons are made only between fertilizer treatments, excluding the control.

P uptake, while a further increment from 30 to 60P resulted in a 1.3-fold increase. The P uptake was significantly higher in Mt Grand than in Taranaki (24.9 vs. 11.5 mg P pot^{-1} ; $P < 0.001$). In both soils, the highest P uptake occurred in the 60P struvite treatment, with uptake values of 41.2 mg P pot^{-1} in Mt Grand and 20.6 mg P pot^{-1} in Taranaki ($P < 0.05$; Figure 3).

3.3 | Relative Agronomic Effectiveness of Struvite

On average, struvite was 49% more effective ($P > 0.05$) than SSP in accumulating P in ryegrass (Table S2). The RAE of struvite in Mt Grand (159%) was higher ($P = 0.026$) than that in Taranaki (137%). Within soils, P rate had no effect on struvite's RAE in

Mt Grand, with no significant differences among rates ($P > 0.05$). In contrast, in Taranaki soil, struvite's RAE at 15P was significantly higher ($P = 0.006$) than at 30P, while no significant differences ($P > 0.05$) were observed between 15P and 60P or between 30P and 60P.

3.4 | Residual Soil Plant-Available Phosphorus

Across treatments, Olsen-P was greater under struvite than SSP (25 vs. 13 mg kg⁻¹; $P < 0.001$; Table 2) and increased progressively with P rate in both soils ($P < 0.001$; Figure 4). Soil type also had a significant effect, with higher Olsen-P observed in Mt Grand than Taranaki (21 vs. 14 mg kg⁻¹; $p < 0.001$).

A significant fertilizer type $\times$ rate interaction ($P < 0.001$) indicated that the response to increasing P rate differed between fertilizers; at Mt Grand, struvite produced consistently higher Olsen-P than SSP at all rates, with differences widening at 60P. In contrast, at Taranaki, fertilizer effects were smaller, with no significant difference at 15P but higher Olsen-P under struvite at 30P and 60P. The interaction between fertilizer type $\times$ rate $\times$ soil type ($P < 0.05$) indicated a stronger increase in Olsen-P with increasing P rate under struvite in Mt Grand soil compared with Taranaki, while SSP showed a more consistent response across soils. This difference was more pronounced at the highest application rate (60P).

4 | Discussion

The application of P in both fertilizers significantly increased the ryegrass yield compared to the corresponding unfertilized

controls, emphasizing the critical role of P for biomass production and optimal physiological function (Khan et al. 2023). Moreover, increases in P rate resulted in yield increases at each rate, following similar patterns for both fertilizers. Ryegrass yield increased over 70% when P application rate increased from 15P to 60P; it seems evident that struvite availability is also influenced by application rate, much like what is observed with soluble fertilizers such as SSP (Katanda et al. 2016; Plaza et al. 2007).

Although average DM yields between the two soils were similar, struvite's advantage was more apparent at low P rates. This suggests a high synchrony between P release from struvite and P acquisition by the plant; at lower concentrations, the slow-release kinetics of struvite are better aligned with the early-season P demands of the ryegrass (Hall et al. 2020; Rech et al. 2019). In contrast, the initial high P concentration from SSP in the soil solution at low rates may lead to a rapid decline in P availability due to immobilization, even before the ryegrass root system is fully established (Khomenko et al. 2024). Specifically, at 15P of struvite, ryegrass yield in Mt Grand soil was 1.44-fold greater than in Taranaki. The low initial available P in the soil (11 mg P kg⁻¹) and the high P retention capacity of the Taranaki soil likely limited P availability at low application rates, which made it insufficient to achieve higher ryegrass yields. These findings emphasize the importance of considering soil-specific characteristics, especially P retention capacity, when evaluating fertilizer application rates and plant response to P inputs (Ros et al. 2020).

While the magnitude of the response differed between soils, struvite significantly improved perennial ryegrass P uptake in both soils. In all cases, P uptake under struvite exceeded that of the unamended control and SSP treatments. These results indicate

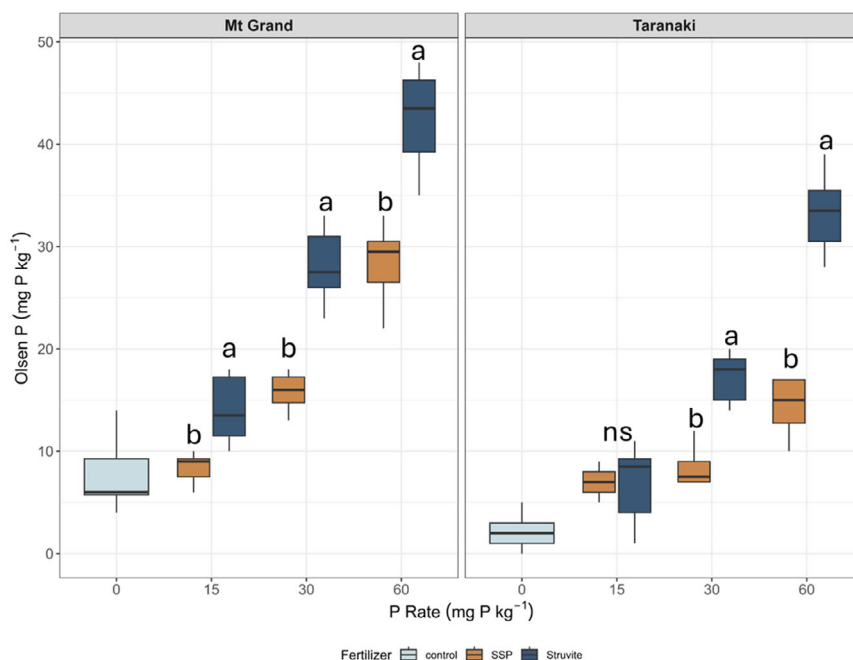


FIGURE 4 | Residual Olsen-P concentration (mg P kg⁻¹) determined in soils from Mt Grand and Taranaki as influenced by applied P rate (0, 15, 30, and 60 mg P kg⁻¹), and fertilizer type (SSP and struvite). Data are presented as boxplots showing the distribution of values for each treatment combination. Different lowercase letters denote significant differences between P sources within each P rate (Tukey, $P < 0.05$). "ns" denotes nonsignificant differences. Comparisons are made only between fertilizer treatments, excluding the control.

that, regardless of struvite's low water solubility (4%), P was rapidly released into the soil solution, likely facilitated by the uniform incorporation of struvite (Degryse et al. 2017); the acidic nature of Mt Grand and Taranaki soils (pH 5.6–5.7) (Cabeza et al. 2011); and the exudation of low-molecular-weight organic acids into the rhizosphere by ryegrass roots, which facilitated the dissolution of struvite by chelating cations and lowering the localized pH, thereby releasing orthophosphate for plant uptake (Huygens and Saveyn 2018; Talboys et al. 2016). This contrasts with the findings of Nongqwenga et al. (2017), who reported that, in a study on maize grown in soils with contrasting textures, the relative performance of struvite compared to SSP was inconsistent between the different P-retention soils. Contrary to our study, they found that struvite was less effective than SSP in soils with extremely high Fe and Al oxide concentrations, presumably due to immediate fixation of the released P.

Differences in ryegrass P uptake between P rates and between fertilizers were more pronounced in Mt Grand soil than in Taranaki. The lower P uptake in Taranaki soil compared to Mt Grand could be mainly attributed to its higher P retention capacity (96%), which limited plant P availability (O'Sullivan et al. 2022). Nevertheless, struvite still resulted in greater P uptake than SSP. This greater P uptake was associated with higher shoot P concentrations under struvite across soils and rates. Shoot P concentration under struvite exceeded the optimum concentration reported for ryegrass (0.21%; Corbett et al. 2022), suggesting enhanced P acquisition rather than differences in biomass production. Differences in fertilizer solubilization dynamics could explain these responses. SSP, a highly water-soluble fertilizer, dissolves rapidly after application and releases phosphate ions into the soil solution, increasing the immediate plant P availability. However, in soils with high concentrations of Fe and Al oxides/hydroxides, such as Taranaki, these ions are quickly adsorbed or precipitated, forming poorly soluble compounds and becoming immobilized shortly after application, reducing their plant availability (Hedley and McLaughlin 2005). Conversely, struvite's low water-solubility (4%) and relatively high solubility in weak organic acids such as citric acid (99%) could have controlled its dissolution and supported a sustained P release that matched ryegrass demand, limiting fixation with the soil and potential nutrient loss (Talboys et al. 2016). This controlled-release behavior may explain why struvite maintained greater shoot P concentrations and P uptake even in the high P-retention Taranaki soil. Such characteristics make struvite particularly advantageous in soils where P fertilization is more challenging, as repeated applications of soluble P fertilizers are often required to overcome the adsorption and subsequent stabilization of the applied P on reactive mineral surfaces (Gomez-Suarez et al. 2020).

Results for the RAE of struvite for plant P uptake showed that the influence of soil type was significant, whereby struvite was 59% more efficient for the Mt Grand soil compared with 37% for the Taranaki soil. This could be mainly attributed to differences in the mineral composition of the soils with respect to the reactions and fate of P added as SSP and struvite. Monocalcium phosphate, the main form of P in SSP, dissolves rapidly on contact with water in soil, forming an acidic (pH 1.0–1.5) saturated P solution ("meta-triple point solution") that reacts with soil mineral components in the immediate vicinity of the fertilizer granule via a

combination of precipitation and adsorption (Lindsay and Stephenson 1959; Nash et al. 2019). On the other hand, the immediate water solubility of struvite is limited, and the consequent slower release of P to the soil solution and subsequent reactions with soil minerals will be very different from monocalcium phosphate and likely dominated by adsorption on oxide and amorphous clay mineral surfaces (Anderson et al. 2020). Thus, the presence of greater quantities of amorphous minerals, principally allophane, in the higher P-retention Taranaki soil may have effectively reduced the plant availability of SSP to a greater extent than struvite compared with the Mt Grand soil. It is important to note that the precise nature and agronomic and environmental implications of the physicochemical reactions and processes that occur at the interface between different P fertilizer granules and the soil ("fertosphere") are poorly understood and require further research (Lombi et al. 2025).

The different reactions of struvite and SSP-derived P in soil and their consequent impact on relative plant P availability are consistent with the fact that concentrations of plant-available P (Olsen-P) determined at the conclusion of the current experiment were consistently and significantly higher for struvite compared with SSP at the higher rates of P input for both soils. This suggests that the contribution of struvite to the more labile fractions of P is greater than that of SSP, which tends to increase the more recalcitrant forms (Gatiboni and Condron 2021; Gu et al. 2021).

5 | Conclusions

The findings of this short-term study demonstrated that struvite is a suitable replacement for SSP in acidic, high-retention, P-temperate grassland soils. Struvite significantly enhances plant P uptake and is particularly effective at lower application rates where nutrient-release synchrony with plant demand is most critical. Moreover, levels of plant-available inorganic P in soil were consistently and significantly higher for struvite, suggesting differences in the reactions between the evaluated fertilizers and the soil components. This indicates that struvite not only provides immediate agronomic benefits but also contributes to a more sustainable P management in New Zealand's intensive pastoral systems. Further field and laboratory research is warranted in temperate grassland systems to investigate and quantify the impacts of other soil properties and processes (e.g., biological activity) and botanical composition (e.g., grass-legume combinations) on the relative effectiveness of struvite as a P fertilizer, as well as assessing the fate of struvite-P across soil P pools over time.

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Conflicts of Interest

The authors report there are no competing interests to declare.

Data Availability Statement

The datasets generated during the current study are available from the corresponding author on reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Nutrient inputs from fertilizers and supplementary nutrient additions for each treatment. **Table S2:** Relative agronomic effectiveness (RAE, %) of struvite compared with SSP (100%) across soils and P rates. Values represent mean RAE (%) of ryegrass P uptake response to struvite, expressed relative to SSP within each factor level. Different lowercase letters within rows indicate significant differences between fertilizers (struvite vs SSP), and different uppercase letters within struvite means indicate differences among levels within a factor (Soil or P rate) ($P < 0.05$).