



Assessment of the relative agronomic effectiveness of struvite fertilizer in a temperate grassland

Florencia DeLucca-Agrelo · Leo Condron · Jim Moir

Received: 8 September 2025 / Accepted: 27 December 2025 / Published online: 9 January 2026
© The Author(s) 2026

Abstract Continued phosphorus (P) inputs are necessary to sustain grassland productivity. Struvite, a sparingly water-soluble P mineral recovered from wastewater, has emerged as an alternative to conventional fertilizers such as water-soluble single superphosphate (SSP). A two-year field study was carried out to investigate the immediate and residual agronomic effectiveness of struvite and SSP in a perennial ryegrass pasture (*Lolium perenne* L.). Phosphorus was applied at 20 and 80 kg P ha⁻¹, alongside unfertilized controls. In Year 1, P addition significantly increased ryegrass dry matter yield by 49% compared with controls. Yields were similar for struvite and SSP at both application rates, although P uptake was significantly higher for struvite (63.4 kg P ha⁻¹) compared with SSP (50.9 kg P ha⁻¹) at the high P rate. In Year 2, the 80 kg P ha⁻¹ struvite treatment maintained significantly higher yield (23.5 Mg ha⁻¹) and P uptake (63.4 kg ha⁻¹) compared with SSP (17.4 Mg ha⁻¹ and 50.9 kg P ha⁻¹). Soil analyses revealed that concentrations of plant-available P were consistently higher for struvite compared with SSP. The findings of this study demonstrated that the

immediate agronomic performance of struvite was equivalent to SSP for low P input, while the immediate and residual effectiveness of struvite at the higher rate of input was superior to SSP. Further research is warranted to determine the relative agronomic effectiveness of struvite for temperate grassland on other soil types under different environmental conditions, together with investigation of the mechanisms responsible for the enhanced plant availability of struvite-P.

Keywords Wastewater · Phosphorus use efficiency · Grassland systems · Legacy phosphorus · Phosphate retention capacity

Introduction

Global food supply depends heavily on phosphorus (P) inputs, a macronutrient vital for plant growth and agricultural productivity. Despite its importance, P management presents a growing sustainability challenge. To maintain productivity and ensure high yields in both crop and pasture systems, inorganic P fertilizers have long been applied (Khan et al. 2023). However, phosphate rock (PR), the primary source of these fertilizers, is a finite and non-renewable resource, with more than 80% of global reserves concentrated in a few countries (United States Geological Survey 2025). The geopolitical concentration of PR, combined with increasing mining costs and fluctuating market fertilizer prices,

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10705-025-10465-x>.

F. DeLucca-Agrelo (✉) · L. Condron · J. Moir
Faculty of Agriculture and Life Sciences, Lincoln
University, Lincoln 7647, New Zealand
e-mail: flor.deluccaagrelo@lincolnuni.ac.nz

raises concerns about long-term access to affordable P fertilizers for farmers, particularly in countries lacking domestic PR reserves (Brownlie et al. 2023).

In addition to concerns over limited global supply, conventional water-soluble P fertilizers such as single superphosphate (SSP) often perform inefficiently in agricultural systems. Low P recovery rates, which result from strong sorption to soil components, poor plant utilization, or losses through leaching and runoff, not only limit crop uptake but also raise environmental concerns (Anderson et al. 2020; McDowell and Haygarth 2024). As a result, much of the applied P becomes unavailable to plants, contributing to the accumulation of P in soils and the eutrophication of freshwater ecosystems. Improving P use efficiency is therefore essential to maintaining and intensifying production while minimizing environmental impacts (Gatiboni et al. 2020).

Perennial ryegrass (*Lolium perenne* L.) is the most widely utilized forage species in temperate pasture systems globally (Blackmore et al. 2016) and constitutes a fundamental component of pastoral-based farming in New Zealand pasture systems (Prout et al. 2025). New Zealand pastoral soils are typically acidic ($\text{pH} \leq 6$) and naturally low in P, with a wide range of P fixation capacities that limit plant-available P (Chen et al. 2003). To maintain productivity, the sector has long relied on SSP fertilizer, with up to 1.5 million tons applied annually (Fertiliser Association of New Zealand 2025; Hall 2023).

Growing sustainability and environmental challenges have intensified efforts to develop a circular P economy. This transition focuses on reducing environmental risks, lowering dependence on phosphate rock fertilizers, and improving nutrient recycling (Cordell and White 2013). Given that recyclable waste streams contain enough P to meet global annual demand, recycling emerges as an essential pathway for strengthening P supply security and closing the P loop (Raniero et al. 2025).

Struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$), a P-rich mineral recovered from wastewater streams, is a potentially agronomic viable P source alternative. Struvite is a slow-release fertilizer characterized by low water-solubility ($< 5\%$) but enhanced dissolution in the presence of organic acids, which could allow a sustained source of plant P availability over time (Erdal et al. 2024; Gu et al. 2021). Its recovery from municipal

and agricultural waste streams contributes to closing the P cycle, reducing dependency on mined PR.

The potential of struvite as a fertilizer has been shown to depend strongly on soil and cultivation conditions (Hertzberger et al. 2020). Most of the existing field trials have focused on cropping systems in neutral to alkaline soils (Benjannet et al. 2020; Hilt et al. 2016; Kokulan et al. 2024; Omidire and Brye 2022; Thiessen Martens et al. 2022). However, the agronomic performance of struvite in grassland systems, particularly those on acidic soils, remains scarce. To our knowledge, very few studies have examined struvite use under these conditions (Karpinska et al. 2024), and research on the residual agronomic effect of a single application is particularly limited.

This study was designed to investigate and quantify the immediate and residual agronomic performance of struvite as a P fertilizer for perennial ryegrass in an acidic soil compared with SSP. Based on previous studies, we expected that the immediate agronomic performance of struvite would be equivalent to SSP; and we hypothesize that due to differences in solubility and reactions in soil, the residual effectiveness of struvite is superior to SSP.

Materials and methods

Site description

A two-year field experiment was conducted from May 2023 at Lincoln University in New Zealand ($43^\circ 38'S$, $172^\circ 28'E$). The climate of the region is temperate, with temperatures ranging from 7 to 18°C , with an average annual precipitation of 663 mm (Macara 2016). The soil at the site is classified as Wakanui silt loam (Typic Immature Pallic Soil, New Zealand classification; Udic Ustochrept, USDA classification). Very little fertilizer had been applied to the site prior to establishment of the experiment, and the site was managed under different crops and pastures, including subterranean clover (*Trifolium subterraneum* L.), maize (*Zea mays* L.), barley (*Hordeum vulgare* L.), and wheat (*Triticum aestivum* L.). Perennial ryegrass was sown in April 2023 at a rate of 20 kg ha^{-1} . Here-with selected chemical characteristics of the topsoil (0–7.5 cm) at establishment: pH (H_2O) 5.6, Olsen-P 8 mg kg^{-1} , organic C 2.5%, total N 0.23%, total P 839 mg kg^{-1} , and P retention capacity 25%. Soil pH

was measured potentiometrically in a 1:2 soil-to-water suspension (Blakemore et al. 1981) using a pH probe (SevenEasy pH meter, Mettler Toledo, USA, Varian 720-ES, Agilent Technologies Inc., USA). Plant-available P (Olsen-P) was determined according to Olsen et al. (1954) using a 1:20 soil-to-extractant ratio, followed by colorimetric detection (Murphy and Riley 1962) on a UV–VIS spectrophotometer (Shimadzu UV-1900i, Japan). Total C and N were measured by Dumas combustion. Total P was obtained via nitric–hydrochloric acid digestion (USEPA 1994) and subsequent ICP-OES analysis. Phosphorus retention capacity was measured following Saunders (1965).

Climate and irrigation

Monthly rainfall, irrigation, and air temperature for the experimental period are presented in Fig. 1. The mean annual temperature over the duration of the experiment was 10.5 °C (2.0 to 21.7 °C), while the mean annual temperature for the historical climate data for the site is 11.4 °C (6.2 and 16.6 °C). The

mean annual temperature for Year 1 was 11.4 °C (2.0–26.1 °C), and for Year 2 the mean annual temperature was 11.8 °C (0.9–23.5 °C). Rainfall in Year 1 was 715 mm plus 414 mm irrigation (total 1129 mm) compared with 1016 mm rainfall and 320 mm irrigation (total 1336 mm) in year 2. Rainfall during the final two months of year 1 was 74 mm compared with 290 mm in year 2 (Fig. 1).

Experimental design and treatments

Eight treatments with four replicated plots (2×5 m) were established in a completely randomized block design. Two P fertilizers (i.e., struvite and SSP) were evaluated at two application rates (20 and 80 kg P ha⁻¹, designated as 20P and 80P, respectively). The experiment required four “control” treatments due to the presence of significant quantities of nitrogen and magnesium in struvite, and sulfur in SSP – these were designated as Control-0, Control-N, Control-Mg, and Control-S. To ensure nutrient balance, all plots receiving P fertilizer also

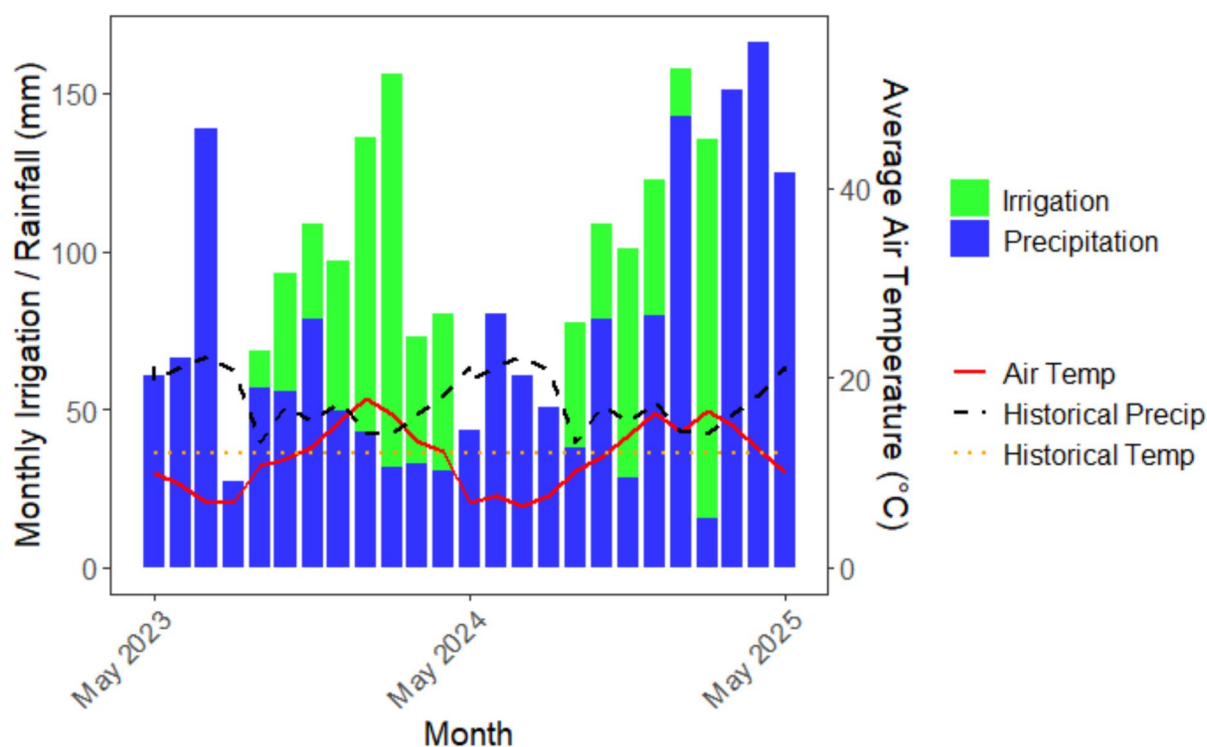


Fig. 1 Monthly mean air temperature, total monthly rainfall and irrigation during the experimental period. Data from historical precipitation and temperature represent the monthly average for the previous 50 years (1972–2022)

received nitrogen (as urea) and sulfur at uniform rates across treatments, considering the amounts of nutrients already applied with the fertilizers (Supplementary Table S1). The struvite used in this study (Emerge®) was derived from municipal wastewater produced by Watercare Auckland (12.3% total P, 99% citric-soluble P, 4% water-soluble P, particle size 0.15–0.25 mm); and the SSP was manufactured by Ballance® (12% total P, 85% citric-soluble P, 90% water-soluble P, particle size ~4 mm). All fertilizers were applied manually to the soil surface and irrigation was applied through a system of sprinkler hoses at 25 mm/h between October and March when the soil moisture content to 20 cm depth reached approximately 25% (permanent wilting point=20%) (NZ Soil Bureau 1968).

Sampling and analysis

Pasture yield cuts were carried out at a sward height of 30 cm using a rotary mower to a residual height of 3 cm. A total of eight cuts were made in the first year and seven during the second year. Plant samples were oven-dried at 65 °C for 72 h to determine dry matter yield (DMY), and the annual yield (Mg ha^{-1}) was calculated as the sum of the consecutive harvests. Dried plant samples were ground <1 mm and analyzed for P by nitric acid-hydrogen peroxide digestion and ICP-OES (Wu et al. 1997).

Plant P uptake was calculated by combining yield and P content data. The relative agronomic effectiveness of struvite in relation to SSP was calculated as according to Vogel et al. (2015):

[Accumulated P uptake struvite / Accumulated P uptake SSP] $\times$ 100.

Soil samples (0–7.5 cm) were taken at the end of each year of the experiment (May 2024 and 2025). Soil samples were dried at 40 °C for 48 h, ground <2 mm, and inorganic P fractions were determined using the sequential extraction method described by Gatiboni and Condon (2021), namely labile P [P extracted by CaCl_2 and Mehlich-3], moderately labile P [P extracted by NaOH], and non-labile P [P extracted by HCl].

Statistical analysis

Statistical analyses were conducted in RStudio V4.5.0 (R Core Team 2023). Prior to the analysis, all data

were tested for normality and homogeneity of variances using Shapiro–Wilk and Levene tests, respectively. Cumulative DMY and P uptake were analyzed using mixed linear models, with fertilizer type and P rate as fixed effects and block as a random effect. Tukey's HSD test was used for pairwise comparisons of treatment means ($P < 0.05$).

To assess statistically significant differences in each soil P fraction among fertilizer treatments within each Year–rate combination, one-way ANOVAs were performed, followed by Tukey's HSD ($P < 0.05$).

Results

Year 1: Ryegrass yield, P uptake, and agronomic effectiveness

Mean annual DMY was 18.1 Mg ha^{-1} and varied from 12.4 Mg ha^{-1} in the 0P control to 25.7 Mg ha^{-1} in the 80P struvite treatment (Table 1). Fertilizer application increased yield (21.9 Mg ha^{-1}) compared with controls (15.9 Mg ha^{-1}), while similar yields were determined for struvite (22.9 Mg ha^{-1}) and SSP (21.3 Mg ha^{-1}). Corresponding data for P uptake clearly showed a significant overall increase in response to P fertilizer input ($49.9 \text{ kg P ha}^{-1}$) compared with control treatments ($29.1 \text{ kg P ha}^{-1}$) (Table 1).

Data presented in Fig. 2 showed there were no significant differences in annual yield between struvite and SSP at both rates of P input. On the other hand, while there was no significant difference in plant P uptake between P fertilizers at the low P rate (42.0 and $43.5 \text{ kg P ha}^{-1}$), uptake from the high P rate was significantly higher for struvite ($63.4 \text{ kg P ha}^{-1}$) compared with SSP ($50.8 \text{ kg P ha}^{-1}$) (Fig. 3). Accordingly, struvite showed significantly higher overall agronomic effectiveness relative to SSP with respect to P uptake (115%), and the relative effectiveness of struvite was greater at the higher rate of P input (125%) than at the lower rate (104%) (Table 2).

Year 2: residual P effect on ryegrass yield and P uptake

The overall average yield was lower for Year 2 than Year 1 (15.8 versus 18.1 Mg ha^{-1}), although yields for the P fertilizer treatments remained significantly

Table 1 Cumulative dry matter yield (DMY) and P uptake of ryegrass for the 2-year experiment, as affected by fertilizer type (struvite, SSP) and P application rate (0, 20, 80 kg P ha⁻¹)

	DMY Year 1 (Mg ha ⁻¹)	DMY Year 2	P uptake Year 1 (kg ha ⁻¹)	P uptake Year 2
Control-0	12.4	12.8	23.8	16.2
Control-N	16.2	11.0	33.9	25.7
Control-Mg	14.4	13.3	29.1	19.8
Control-S	15.4	11.8	30.4	17.2
<i>Struvite</i>				
20	20.2	20.2	43.5	44.4
80	25.7	23.5	63.4	59.7
<i>SSP</i>				
20	20.1	17.3	42.0	34.9
80	22.6	17.4	50.9	41.7
ANOVA	<i>P</i> value			
Fertilizer-P	<0.0001	<0.0001	<0.0001	<0.0001
Rate	<0.0001	ns	<0.0001	<0.0001
Fertilizer×Rate	ns	ns	0.0121	ns

Control treatments were included to assess the effect of individual nutrient additions. Control-0, received no fertilizer; Control-N, received nitrogen only; Control-Mg, received magnesium only; and Control-S, received sulfur only

ns. Not significant, $P > 0.05$. Fertilizer-P refers to the fertilizer type factor

higher (19.6 Mg ha⁻¹) compared with the controls (12.2 Mg ha⁻¹) (Table 1). Overall, cumulative yield in struvite treatments was higher ($P=0.02$) than that of SSP treatments (21.8 and 17.3 Mg ha⁻¹, respectively). While yields for the 20P struvite and SSP treatments were similar (20.2 and 17.4 Mg ha⁻¹), at the higher P rate struvite yield was significantly higher (23.4 Mg ha⁻¹) than SSP (17.3 Mg ha⁻¹) (Fig. 2). Phosphorus uptake was, however, significantly higher for struvite compared with SSP at both the low (44.4 kg P ha⁻¹ vs. 34.9 kg P ha⁻¹) and high (59.7 kg P ha⁻¹ vs. 41.7 kg P ha⁻¹) P input rates (Fig. 3), and so the overall agronomic effectiveness of struvite was 37% higher than SSP (Table 2).

Soil phosphorus

Figure 4 shows data for the different soil inorganic P fractions (labile, moderately labile, and non-labile) determined in topsoil fertilized with struvite and SSP at the end of each year of the experiment. At the end of Year 1, concentrations of labile P and moderately labile P were markedly and significantly higher at the high P input rate (P80) for struvite (68 and 78 mg P kg⁻¹) compared with SSP (45 and

58 mg P kg⁻¹). Concentrations of all soil P fractions were lower at the end of Year 2 compared with Year 1, although levels of labile P and moderately labile P remained significantly higher for the P80 struvite treatment than SSP.

Discussion

Comparable immediate agronomic performance of struvite and SSP

As expected, given the low plant available P status of the soil, P fertilizer inputs increased plant yields on average by 49% compared with control treatments, demonstrating the essential role of P fertilization in promoting forage productivity (Sheil et al. 2016). Our measured DMY values were comparable to those reported in other irrigated ryegrass experiments conducted in this region of New Zealand (Cotching and Burkitt 2011; Michel et al. 2014). Furthermore, the absence of significant differences among the control treatments confirms that the observed yield responses were specifically attributable to P addition.

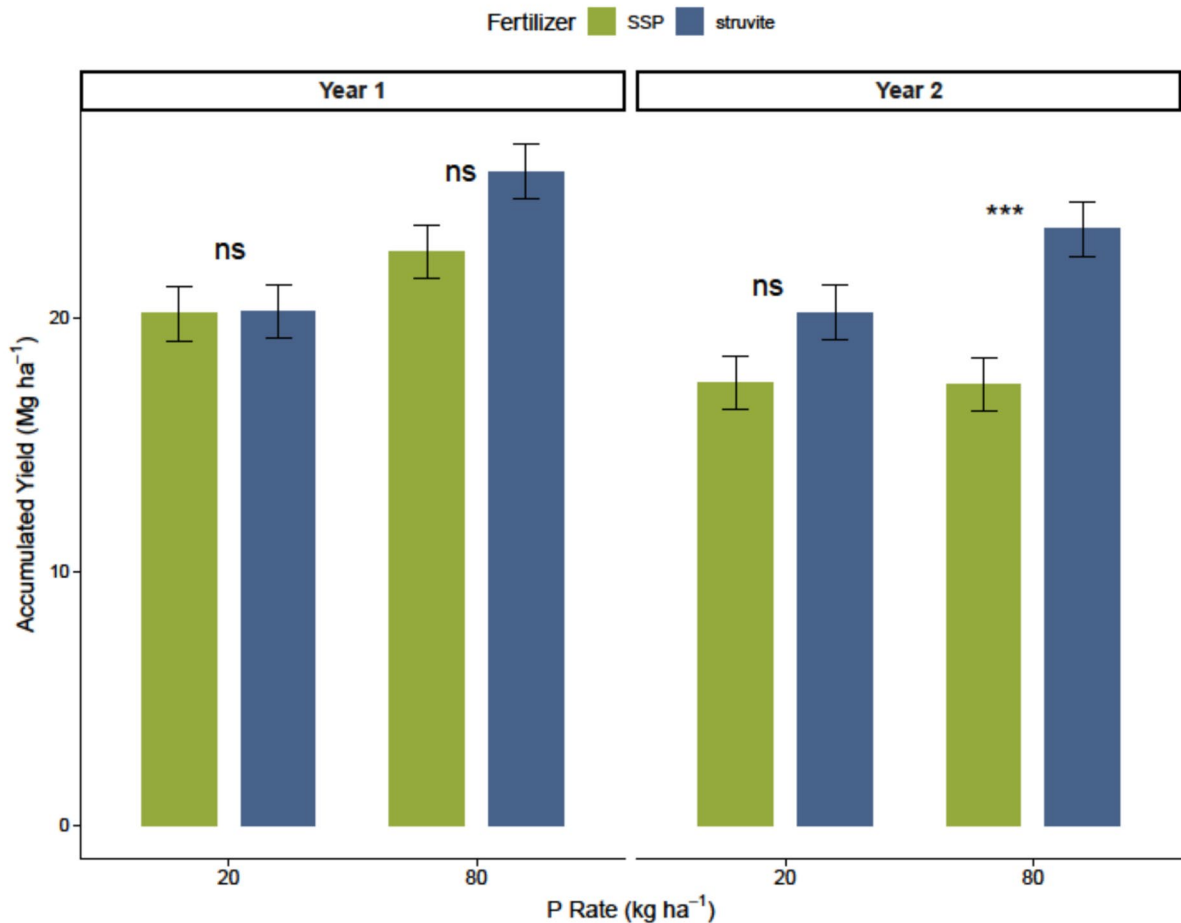


Fig. 2 Accumulated dry matter yield by ryegrass over two years as affected by fertilizer type (SSP or struvite) and P application rate (20 or 80 kg P ha⁻¹). Bars represent means and

error bars represent standard errors (n=4). Asterisks indicate significant differences between fertilizers within each P rate according to Tukey's test (*** $P < 0.01$; ns = not significant)

Struvite application in the first year resulted in DMY comparable to that of SSP. These findings demonstrated that struvite was as effective as SSP in supplying P to support perennial ryegrass growth in the year of application. Despite the low water solubility of struvite (4%), it effectively supplied P at a rate that did not compromise ryegrass yield and provided similar immediate agronomic benefits in this experiment.

The results of this study align with previous long-term field studies evaluating struvite as a P fertilizer for ryegrass on soils with comparable texture and pH. For instance, O' Donnell et al. (2022) reported comparable ryegrass DMY between struvite and conventional fertilizers during the first year of a three-year field trial conducted in a P-deficient sandy-loam soil.

Likewise, Khomenko et al. (2023) and Karpinska et al. (2024) found no yield differences between struvite and SSP in the initial year of evaluation in grassland systems. However, it is important to note that in those studies, struvite was re-applied every year; therefore, any enhanced performance observed in the subsequent years cannot be attributed solely to residual effects from the initial application.

Struvite superior residual P effect

In the second year of the study, where no P fertilizer was applied, a significant residual effect of the initial fertilization was observed. Struvite continued to produce higher DMY than both the controls and SSP, and

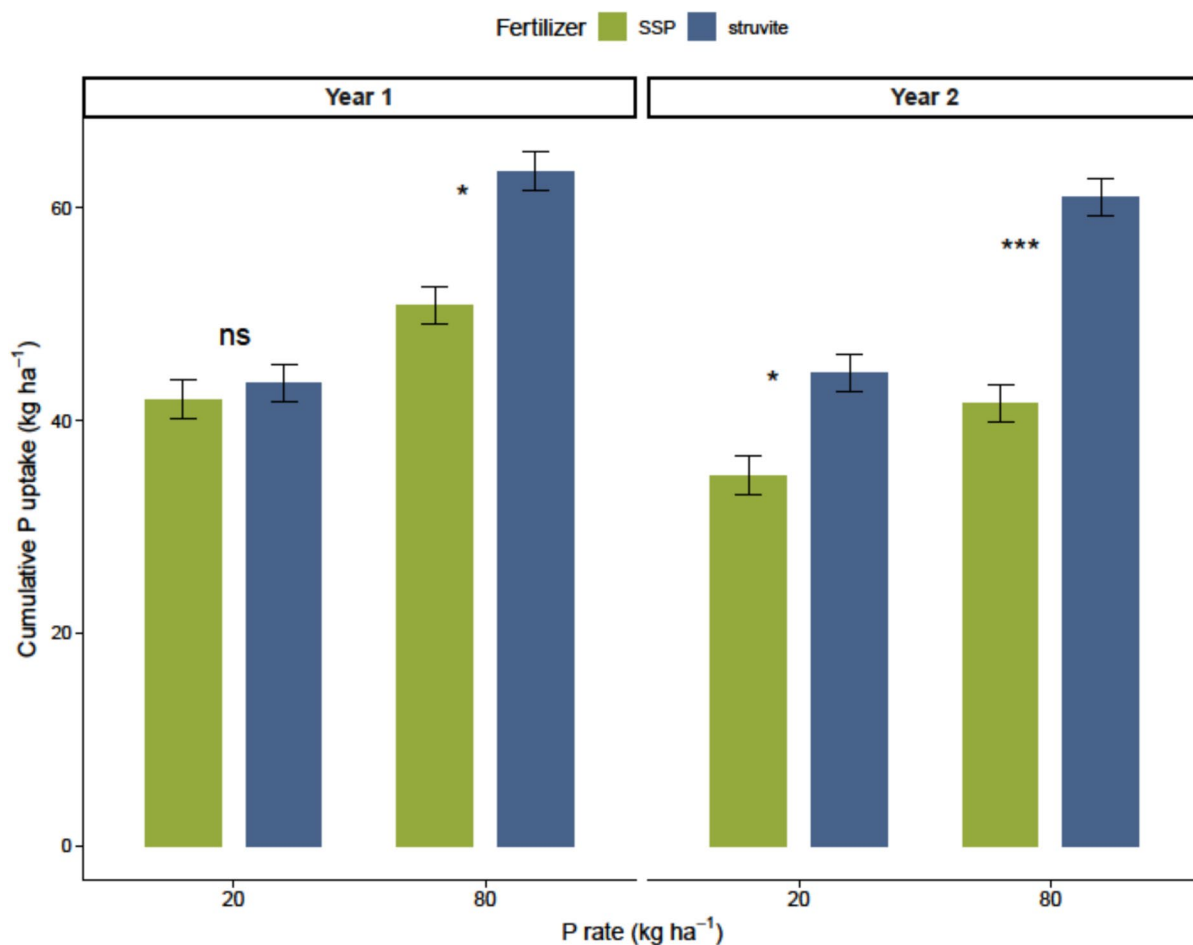


Fig. 3 Cumulative P uptake by ryegrass over two years as affected by fertilizer type (SSP or struvite) and P application rate (20 or 80 kg P ha⁻¹). Bars represent means and error bars

represent standard errors (n=4). Asterisks indicate significant differences between fertilizers within each P rate according to Tukey's test (* $P < 0.05$; *** $P < 0.001$; ns = not significant)

Table 2 Mean relative agronomic effectiveness (%) of struvite in relation to SSP by applied P rate in ryegrass P during the two-year experiment

	Year 1		Year 2	
	P rate (kg ha ⁻¹)			
	20	80	20	80
Struvite	104 ^a	125 ^a	127 ^a	147 ^a
SSP	100 ^a	100 ^b	100 ^b	100 ^b

Within each year, different lowercase letters indicate significant differences between fertilizers at a given P rate (Tukey, $P < 0.05$)

the differences were greater for the high P rate (80P), where struvite produced 6.1 Mg ha⁻¹ more than SSP. These results demonstrate the potential yield benefits of struvite as an alternative P source for temperate perennial pastures. The gradual release of P from struvite due to its low water solubility and high solubility in the presence of organic acids (99%) is likely promoted by root exudation from actively growing perennial ryegrass, synchronizing P release with plant demand (Gu et al. 2021; Talboys et al. 2016).

Few studies have examined the long-term effect of struvite under field conditions, and even fewer have evaluated the residual effect of a single application of struvite in consecutive years (Hertzberger et al. 2020). However, our findings are consistent with

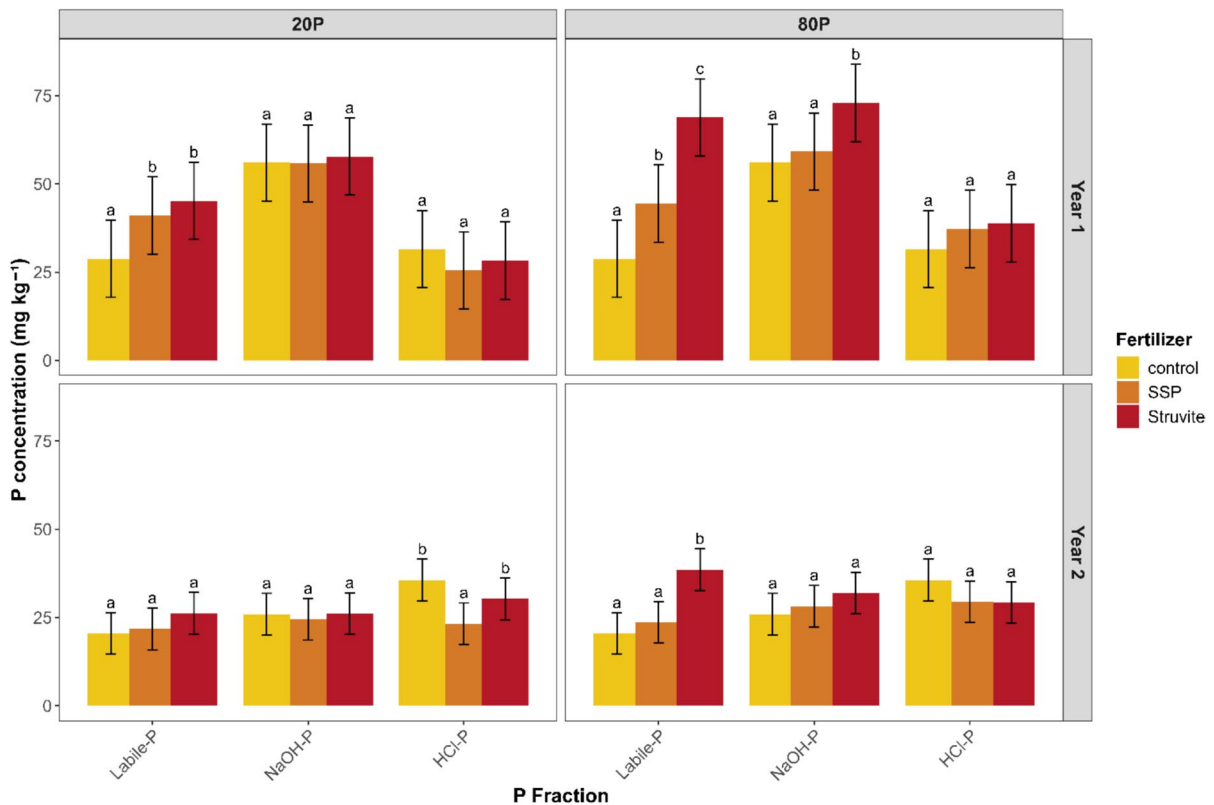


Fig. 4 Soil P fractions (labile-P, NaOH-P, HCl-P) as affected by fertilizer type (SSP or struvite) and P application rate (20 or 80 kg P ha⁻¹) at the end of each year (Year 1, Year 2). Bars

represent means, and error bars represent standard errors (n=4). Different lowercase letters indicate significant differences between fertilizers at a given P fraction (Tukey, $P < 0.05$)

those reported by Thiessen Martens et al. (2022), who investigated the long-term effects of a single struvite application to a lucerne field growing in an alkaline soil. In that study, a significant yield response was observed in the first year after struvite fertilization, and this effect persisted throughout the three-year evaluation period, with lucerne yields averaging 1.92-fold greater than the control without added P.

Perennial ryegrass yield improved with increasing P rates, and the magnitude of the increase for struvite doubled that from SSP. Few field studies have examined the effect of different P rates on struvite performance as a P fertilizer. Hilt et al. (2016) in a multi-year field experiment of lucerne in an alkaline soil found a significant response in DMY for increasing the P rate from 60 to 122 kg P ha⁻¹, and the yields of struvite treatments were comparable to those of MAP at each rate. Likewise, Thiessen Martens et al. (2022) also found a significant response of lucerne to increasing P rates. In their study, the response to

increasing from 0 to 90P was a 1.6-fold greater yield in the first year of evaluation. While the mechanisms governing struvite dissolution are still being clarified, its P availability appears to increase as application rate increases, consistent with what is observed with soluble P fertilizers (Katanda et al. 2016).

Plant P uptake and residual effectiveness of struvite-P

Plant P uptake in Year 1 closely mirrored the patterns observed for DMY, with fertilized treatments accumulating on average 20.6 kg P ha⁻¹ more than the unfertilized controls. At the 80P rate, struvite resulted in greater P uptake than SSP, consistent with its higher relative agronomic effectiveness. However, 20P treatments were more efficient at converting absorbed P into biomass than 80P. The greater P uptake was observed at the higher application rate (80P), but with lower effectiveness in terms of biomass produced per unit of P. When P availability is

high, plants may continue to accumulate P beyond what is needed for growth, resulting in smaller proportional increases in dry matter yield (Penn et al. 2022). This decline in P use effectiveness at higher rates is particularly important in resource-limited systems, where optimizing both P uptake and utilization is essential for sustainable fertilizer management, highlighting the need to identify an optimal application rate. Moreover, the decline in P use effectiveness at the 80P rate could also reflect nutrient co-limitation by nitrogen (Agren et al. 2012). Once ryegrass demand for P was satisfied, further increases in biomass production would likely have been constrained by the availability of nitrogen, thereby reducing the effectiveness of P conversion into yield.

Year 2 results further support the agronomic value of struvite, as demonstrated by its significant residual effect on pasture P uptake. These results suggest that struvite provides a more continuous P supply aligned with plant demand, possibly due to its gradual dissolution and better synchronization with plant uptake patterns (Gu et al. 2021; Valle et al. 2022). In contrast, SSP releases P rapidly, which makes the nutrient immediately available to plant uptake, but at the same time, it is more susceptible to losses or soil fixation shortly after application (Yang and Yang 2021). These contrasting behaviors may explain the superior effectiveness of struvite in promoting plant P uptake over time (Withers et al. 2014). Even one year after application, struvite remained more effective than SSP, reinforcing its potential to reduce fertilizer inputs over time. Together, these findings emphasize the residual agronomic value of struvite as a P fertilizer and support its use in longer-term P management strategies, particularly in temperate perennial pasture systems where a low application frequency of P fertilizers is desirable.

Struvite enhances labile-P and sustains soil P availability over time

Soil labile-P and NaOH-P declined from Year 1 to Year 2, reflecting ryegrass P uptake and depletion of both fertilizer-derived and native soil P. Higher labile-P under struvite, particularly at 80P, indicates that struvite releases P more gradually than SSP, thereby maintaining soil P availability for longer periods.

The drawdown of NaOH-P from struvite further supports that struvite availability is strongly regulated

by plant activity (Raniero et al. 2022), and therefore, its use as a slow-release fertilizer with potential residual benefits in subsequent years. In contrast, SSP also increased soil labile-P but to a lesser extent than struvite, consistent with its rapid solubility and the greater likelihood of P being either fixed into less available pools or lost from the soil–plant system. These processes may explain the contrasting behavior of SSP and struvite, but the specific mechanisms of P retention and loss require further investigation.

The relatively stable concentrations of HCl-P across rates suggest that more recalcitrant soil P pools were largely unaffected by short-term fertilization, whereas labile-P and NaOH-P were more sensitive indicators of immediate fertilizer effects and potential plant P availability.

Conclusions

The findings of this study clearly demonstrated that sparingly water-soluble struvite was an effective P fertilizer for a perennial ryegrass pasture under acidic soil conditions, and the immediate and residual effectiveness of struvite was significantly greater than SSP at the higher rate of P input. These results position struvite as a promising P source for these productive systems. However, further work is needed to clarify the chemical and biological processes that control the availability of struvite-P and to identify the mechanisms responsible for the enhanced plant availability of struvite-P relative to SSP. Establishing optimal struvite application rates is also critical for efficient nutrient management. The high soil labile P concentrations observed under struvite indicate that this P source can potentially supply P over successive growing cycles. However, long-term studies are required to confirm whether a single application of struvite is sufficient across multiple seasons and whether repeated applications contribute to legacy P pools in the same way as water-soluble P fertilizers.

Acknowledgements We want to thank Colby Crawford for his technical assistance. We also thank Lenir Gotz, Felipe Deifel, Caterina Campese, Kirill Bogdanov, and Carys Luke for their help during sampling.

Author's Contributions F.D.A., Conceptualization, Methodology, Investigation, Data curation and Analysis, Writing—Original Draft, Writing—Reviewing and Editing,

Visualization. L.C, Conceptualization, Methodology, Writing—Reviewing and Editing, Supervision. J.M, Conceptualization, Methodology, Writing—Reviewing and Editing, Supervision.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions.

Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Agren GI, Wetterstedt JAM, Billberger MFK (2012) Nutrient limitation on terrestrial plant growth – modeling the interaction between nitrogen and phosphorus. *New Phytol* 194:953–960
- Anderson R, Brye KR, greenlee LF, Gbur E (2020) Chemically precipitated struvite dissolution dynamics over time in various soil textures. *Agric Sci* 11:567–591
- Benjannet R, Nyranzeza J, Khiari L, Cambouris A, Fuller K, Hann S, Ziadi N (2020) Potato response to struvite compared with conventional phosphorus fertilizer in Eastern Canada. *Agron J* 112:1360–1376
- Blackmore T, Thorogood L, Skøt L, McMahon R, Powell W and Hegarty M (2016) Germplasm dynamics: the role of ecotypic diversity in shaping the patterns of genetic variation in *Lolium perenne*. *Scientific Reports* 6
- Blakemore L C, Searle P L and Daly B K (1981) Methods for chemical analysis of soils. Department of Scientific and Industrial Research, Lower Hutt. pp. 102
- Brownlie WJ, Sutton MA, Cordell D, Reay DS, Heal KV, Withers PJA, Vanderbeck I, Spears B (2023) Phosphorus price spikes: a wake-up call for phosphorus resilience. *Front Sustain Food Syst*. <https://doi.org/10.3389/fsufs.2023.1088776>
- Chen CR, Sinaj S, Condrón LM, Frossard E, Sherlock RR, Davis MR (2003) Characterization of phosphorus availability in selected New Zealand grassland soils. *Nutr Cycl Agroecosyst* 65:89–100
- Cordell D, White S (2013) Sustainable phosphorus measures: strategies and technologies for achieving phosphorus security. *Agronomy*. <https://doi.org/10.3390/agronomy3010086>
- Cotching W, Burkitt LL (2011) Soil phosphorus effects on ryegrass (*Lolium perenne* L.) production on a Hydrosol in Tasmania. *N Z J Agric Res*. <https://doi.org/10.1080/00288233.2011.591809>
- Erdal I, Yazic H, Ekinci K, Armagan S, Yaylaci C, Mejri R, Salih Kumbul B (2024) Comparison of struvite as a P source with chemical fertilizers and evaluation of additional contribution to growth and mineral nutrition of lettuce grown on acidic and calcareous soils. *J Soil Sci Plant Nutr* 24:3315–3328
- Fertiliser Association of New Zealand (2025) Fertiliser Use in NZ.
- Gatiboni LC, Brunetto G, Pavinato PS, George TS (2020) Editorial: legacy phosphorus in agriculture: role of past management and perspectives for the future. *Front Earth Sci*. <https://doi.org/10.3389/feart.2020.619935>
- Gatiboni LC, Condrón LM (2021) A rapid fractionation method for assessing key soil phosphorus parameters in agroecosystems. *Geoderma* 385:114893
- Gu C, Zhou Q, Cusick R D and Margenot A J (2021) Evaluating agronomic soil phosphorus test for soils emended with struvite. *Geoderma* 399
- Hall R (2023) New Zealand Fertilizer and Products. USDA, New Zealand
- Hertzberger AJ, Cusick RD, Margenot AJ (2020) A review and meta-analysis of the agricultural potential of struvite as a phosphorus fertilizer. *Soil Sci Soc Am J* 84:653–671
- Hilt K, Harrison J, Bowers K, Stevens R, Bary A, Harrison K (2016) Agronomic response of crops fertilized with struvite derived from dairy manure. *Water Air Soil Pollut* 227:388
- Karpinska A, Kakouli-Duarte T, Ashekuzzaman S M, Byrne J, Schmalenberger A, Forrester P J (2024) Plant and soil effects of alternative sources of phosphorus over three year of application. *agronomy* 14
- Katanda Y, Zvomuya F, Cicek N (2016) Hog-manure-recovered struvite: effects on canola and wheat biomass yield and phosphorus use efficiencies. *Soil Sci Soc Am J* 80:135–146
- Khan F, Siddique AB, Shabala S, Zhou M, Zhao C (2023) Phosphorus plays key roles in regulating plants' physiological responses to abiotic stresses. *Plants*. <https://doi.org/10.3390/plants12152861>
- Khomenko O, Fenton O, Leahy JJ, Daly K (2023) Temporal changes in labile soil phosphorus pools in grassland receiving P recycled from dairy processing sludge. *Soil Secur*. <https://doi.org/10.1016/j.soisec.2023.100110>
- Kokulan V, Schneider K, Macrae ML, Wilson H (2024) Struvite application to field corn decreases the risk of environmental phosphorus loss while maintaining crop yield. *Agric Ecosyst Environ*. <https://doi.org/10.1016/j.agee.2024.108936>

- Macara GR (2016) The climate and weather of Canterbury. In NIWA Science and Technology Series, NIWA
- McDowell RW, Haygarth P (2024) Reducing phosphorus losses from agricultural land to surface water. *Curr Opin Biotechnol*. <https://doi.org/10.1016/j.copbio.2024.103181>
- Michel A J, Brown H E, Teixeira E I, Meeken E D, Smaley S, George M J, Gillespie R N (2014) The production and water extraction of lucerne and ryegrass under different irrigation frequencies on a shallow soil. *Proceedings of the New Zealand Grassland Association* 76, 221–228.
- Murphy J, Riley JP (1962) A modified single solution method for the determination of phosphate in natural waters. *Anal Chem Acta* 27:31–36
- NZ Soil Bureau (1968) Soils of New Zealand Part 3. New Zealand Department of Scientific and Industrial Research, Wellington
- O' Donnell C, Barnett D, Harrington J, Power N (2022) The extended effect of top-dressed recovered struvite fertiliser on residual Irish grassland soil phosphorus levels compared to commercial phosphorus fertiliser. *Agronomy* 12.
- Olsen S R, Cole C V, Watanabe F S, Dean L A (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Ed. USDA. U.S. Government Printing Office, Washington D.C.
- Omidire NS, Brye KR (2022) Wastewater-recycled struvite as a phosphorus source in a wheat–soybean double-crop production system in eastern Arkansas. *Agrosys Geosci Environ*. <https://doi.org/10.1002/agg2.20271>
- Penn C, Camberato J, Wiethorn MA (2022) How much phosphorus uptake is required for achieving maximum maize grain yield? Part 1: Luxury consumption and implications for yield. *Agronomy*. <https://doi.org/10.3390/agronomy13010095>
- Prout BM, Mtandavari YF, Jauregui R, MacLean P, Shi S, Lee CK, Griffiths WM, Hume DE, Bell NL (2025) Influence of *Epichloë* on the microbiota of established *Lolium perenne* pastures in Aotearoa, New Zealand. *Phytobiomes J* 9:219–230
- R Core Team (2023) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria
- Raniro HR, Bettoni Teles AP, Adam C, Pavinato PS (2022) Phosphorus solubility and dynamics in a tropical soil under sources derived from wastewater and sewage sludge. *J Environ Manage*. <https://doi.org/10.1016/j.jenvman.2021.113984>
- Raniro HR, Serrano-Gomez J, Mort HL, Kalpakchiev T, Kooij J, Zhao Y, Valença RM, Magaya S, Guerrero-Esquivel AJ, Korving L, Wilfert P, Prot T, Martin-Ortega J, Müller-Stöver DS, van Loosdrecht M, Cordell D, Santner J, Liimatainen H, Hermann L, Scholz M, Christensen ML, van der Bom F, Raymond NS, Jensen SK, Smith F, Reitzel K (2025) Overcoming recycling barriers to transform global phosphorus management. *Nature Rev Earth Environ* 7:1–8
- Saunders WMH (1965) Phosphate retention in New Zealand soils and its relation to free sesquioxides, organic matter and other soil properties. *New Zealand Journal of Agricultural Research*. *N Z J Agric Res* 8:30–57
- Sheil TS, Wall DP, Culleton N, Murphy J, Grant J, Lalor STJ (2016) Long-term effects of phosphorus fertilizer on soil test phosphorus, phosphorus uptake and yield of perennial ryegrass. *J Agric Sci* 154:1068–1108
- Talboys PJ, Heppell J, Roose T, Healey JR, Jones DL, Withers PJA (2016) Struvite: a slow-release fertiliser for sustainable phosphorus management? *Plant Soil* 401:109–123
- Thiessen Martens JR, Entz MH, Schneider KD, Zvomuya F, Wilson HF (2022) Response of organic grain and forage crops to struvite application in an alkaline soil. *Agron J* 114:795–810
- United States Geological Survey U (2025) Mineral Commodity Summaries 2025: Phosphate, Rock. U S G Survey, Reston, VA
- USEPA (1994) Method 200.2: Sample preparation procedure for spectrochemical analyses of total recoverable elements. U.S. Environmental Protection Agency, Cincinnati, Ohio
- Valle SF, Giroto AS, Dombinov V, Robles-Aguilar AA, Jablonowski ND, Ribeiro C (2022) Struvite-based composites for slow-release fertilization: a case study in sand. *Sci Rep*. <https://doi.org/10.1038/s41598-022-18214-8>
- Vogel T, Nelles M, Eichler-Löbermann B (2015) Phosphorus effects of recycled products from municipal wastewater on crops in a field experiment. *Plant Soil Environ* 63:475–482
- Withers PJA, Sylvester-Bradley R, Jones DL, Healey JR, Talboys PJ (2014) Feed the crop not the soil: rethinking phosphorus management in the food chain. *Environ Sci Technol* 48:6523–6530
- Wu S, Feng X, Wittmeier A (1997) Microwave digestion of plant and grain reference materials in nitric acid or a mixture of nitric acid or a mixture of nitric acid and hydrogen peroxide for the determination of multi-elements by inductively coupled plasma mass spectrometry. *J Anal at Spectrom* 12:797–806
- Yang M, Yang H (2021) Utilization of soil residual phosphorus and internal reuse of phosphorus by crops. *PeerJ*. <https://doi.org/10.7717/peerj.11704>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.