Recycled nutrients supply phosphorus and improve ryegrass yields on phosphorus-depleted soil

Authors: Nicksy, Jessica, Amiro, Brian, and Entz, Martin

Source: Canadian Journal of Soil Science, 101(3) : 565-569

Published By: Canadian Science Publishing

URL: https://doi.org/10.1139/cjss-2021-0004

SHORT COMMUNICATION

Recycled nutrients supply phosphorus and improve ryegrass yields on phosphorus-depleted soil

Jessica Nicksy, Brian Amiro, and Martin Entz

Abstract: Recycling phosphorus (P) within the food system is fundamental to long-term sustainability. This greenhouse study compared three sources of recycled P — struvite precipitated from municipal wastewater, black soldier fly frass from food waste, and anaerobic digestate of food waste — to mono-ammonium phosphate (MAP), compost, and a control. Italian ryegrass (*Lolium multiflorum*) was harvested four times during a 123 d trial from P-depleted soil. In nitrogen (N) sufficient conditions, all amendments significantly increased cumulative ryegrass yields compared with the control and were not significantly different from MAP. Relative P supply was frass = MAP > struvite ≥ compost ≥ digestate >> control. The recycled nutrient sources tested show promise as sustainable P sources.

Key words: organic management, phosphorus, recycled nutrients, nutrient cycling, circular economy.

Résumé : Pour parvenir à la pérennité à long terme, on doit absolument recycler le phosphore (P) dans la chaîne alimentaire. Les auteurs ont procédé à une étude en serre pour comparer trois sources de P recyclé — précipité de struvite des eaux usées municipales, excréments de la mouche soldat noire nourrie de résidus d'aliments, digestat anaérobique de déchets alimentaires — au phosphate monoammonique (MAP), au compost et à un témoin. L'ivraie multiflore (*Lolium multiflorum*) a été récoltée à quatre reprises durant l'expérience de 123 j sur un sol carencé en P. Quand la concentration d'azote est adéquate, les amendements augmentent tous significativement le rendement cumulatif de l'ivraie, comparativement à celui de la parcelle témoin, et les résultats ne diffèrent pas sensiblement de ceux obtenus avec le MAP. La teneur relative en P suit la séquence que voici : excréments = MAP > struvite ≥ compost ≥ digestat >> témoin. Les oligoéléments recyclés pourraient être prometteurs en tant que source durable de P. [Traduit par la Rédaction]

Mots-clés : gestion biologique, phosphore, oligoéléments recyclés, cycle des oligoéléments, économie circulaire.

Introduction

Phosphorus (P) plays a pivotal and paradoxical role in the food–energy–water nexus; it is an essential nutrient for the crop growth, but also a harmful pollutant causing eutrophication of water bodies when it leaves the agricultural system (Jarvie et al. 2015). Mined phosphate rock, used to make phosphorus fertilizers and applied directly in organic systems, is a non-renewable resource that may be depleted in 70–140 yr (Li et al. 2018). Recycled sources of P must become the norm to ensure long-term food system sustainability. Recycled nutrients may be especially important on Canadian organic farms, which often suffer from P depletion due to negative P balances (Schneider et al. 2017). Nutrients derived from recycled sources remain understudied compared with conventional mined fertilizers or manures, particularly in terms of their P properties.

The present greenhouse study assessed nutrient availability from three recycled sources commercially available in Canada — struvite, frass, and anaerobic digestate — applied to a low-P Prairie soil. Struvite is a phosphate mineral that is extracted from animal or municipal wastewater. The struvite used in the study is municipal in origin, with a median granule size of 0.9 mm. Reviews have found that struvite has good P availability compared with conventional fertilizers, but that it may be less effective in high-pH soils due to its low solubility at high pH (Möller et al. 2018;

Received 13 January 2021. Accepted 23 March 2021.

J. Nicksy and B. Amiro. Department of Soil Science, University of Manitoba, Winnipeg, MB R3T 2N2, Canada.

M. Entz. Department of Soil Science, University of Manitoba, Winnipeg, MB R3T 2N2, Canada; Department of Plant Science, University of Manitoba, Winnipeg, MB R3T 2N2, Canada.

Corresponding author: Jessica Nicksy (email: nicksyj@myumanitoba.ca).

Hertzberger et al. 2020). Struvite is currently allowed as an organic amendment in Canada when it is sourced from animal or plant wastes. The inclusion of municipal waste struvite will likely be reviewed in the future.

The frass used in this study was the waste product of black soldier fly (BSF) larvae (*Hermetia illucens*) fed a diet of pre-consumer urban food waste. Few studies exist on the fertilizer potential of BSF frass. Kebli and Sinaj (2017) conducted a pot study on three soils using lettuce and ryegrass, and found that frass applied based on a nitrogen rate consistently improved yields over the control in a sandy, low pH soil. Yields were similar to or greater than the mineral fertilizer. The present study is the first, to our knowledge, to focus specifically on the P fertilizer attributes of frass.

The anaerobic digestate in this study is a dried and pelletized solid fraction of food retail and food processing waste digested in the absence of oxygen. Most studies on the fertilizer properties of digestate use animal waste or sewage sludge digestates and (or) focus on nitrogen (N) supply. Brod et al. (2015) characterized P fractions of liquid and solid food waste digestate, and used a ryegrass pot study to test P uptake. They found a higher proportion of HCl-soluble recalcitrant P in the solid digestate, a lower P recovery of solid digestate compared with liquid digestate or synthetic P, and lower ryegrass yields for solid digestate compared with liquid digestate or synthetic P at the earliest harvest time. This indicates lower P availability in solid P digestate compared with mineral fertilizer, and a high proportion of HCl-soluble recalcitrant P, which suggests the availability of digestate P may be limited at high pH.

We hypothesized that nutrients from recycled sources would improve ryegrass yields and P uptake compared with the control, and that they would have similar yields and P uptake compared with a conventional fertilizer under conditions of N sufficiency. A secondary hypothesis was that nutrient sources with a lower N:P ratio (e.g., struvite) would yield less than those with high N:P ratio (e.g., frass) when N was not supplied and amendments were applied at a constant P rate, due to N supply from the amendment itself. We assessed these hypotheses by comparing the nutrient sources with or without the addition of non-limiting N fertilizer.

Materials and Methods

Nutrient sources

Struvite, frass, and digestate were compared with a common conventional nutrient source (mono-ammonium phosphate, MAP) and a common organic nutrient source (aerobic compost, predominantly horse manure, and bedding). Total nutrient concentrations for MAP (110 $g \cdot kg^{-1}$ N, 230 $g \cdot kg^{-1}$ P) and struvite (50 $g \cdot kg^{-1}$ N, 120 $g \cdot kg^{-1}$ P) were based on manufacturer specifications. Analyses for the organic-matter-based amendments, digestate (38 $g \cdot kg^{-1}$ N, 28 $g \cdot kg^{-1}$ P, 4.0 $g \cdot kg^{-1}$ K, 350 $g \cdot kg^{-1}$ C, 80 $g \cdot kg^{-1}$ water), frass (32 $g \cdot kg^{-1}$ N, 8.7 $g \cdot kg^{-1}$ P, 8.7 $g \cdot kg^{-1}$ K, 400 $g \cdot kg^{-1}$ C, 90 $g \cdot kg^{-1}$ water), and compost (7.1 $g \cdot kg^{-1}$ N, 2.3 $g \cdot kg^{-1}$ P, 5.0 $g \cdot kg^{-1}$ K, 89 $g \cdot kg^{-1}$ C, 180 $g \cdot kg^{-1}$ water), were conducted by Agvise Laboratories, ND, USA.

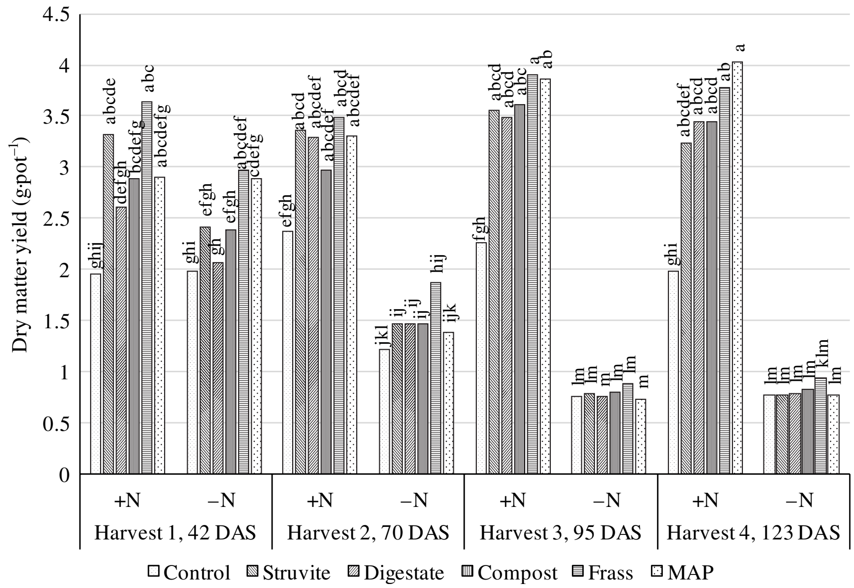
Experimental setup

The greenhouse study was conducted using a P-deficient soil with Italian ryegrass (*Lolium multiflorum*) as a bioassay crop. The soil was a Gleyed Rego Black Chernozem, collected from the 0–15 cm layer at a site under long-term organic management, with a clay texture, 35 $kg \cdot ha^{-1}$ nitrate-N, 3 $mg \cdot kg^{-1}$ Olsen-P, 312 $mg \cdot kg^{-1}$ K, 40 $kg \cdot ha^{-1}$ Cl, 27 $kg \cdot ha^{-1}$ S, 1.3 $mg \cdot kg^{-1}$ B, 0.6 $mg \cdot kg^{-1}$ Zn, 18.7 $mg \cdot kg^{-1}$ Fe, 1086 $mg \cdot kg^{-1}$ Mn, 0.96 $mg \cdot kg^{-1}$ Cu, 1086 $mg \cdot kg^{-1}$ Mg, 6622 $mg \cdot kg^{-1}$ Ca, 54 $g \cdot kg^{-1}$ organic matter, and a soil pH value of 8.1 based on analysis by Agvise Laboratories, Northwood, ND, USA. The soil was coarse sieved (approximately 15 mm), homogenized in a cement mixer, and added to 15 cm diameter pots at a rate of 1914 g dry soil per pot.

The experiment used a two-factor fully-factored randomized complete block design with four replicates. The first factor was phosphorus source, with five amendments and a non-amended control. The second factor was nitrogen fertilization, with pots receiving N fertilizer (identified as +N) and pots not receiving N fertilizer (identified as −N). Amendments were thoroughly mixed with the top 5 cm of the soil to ensure early root access to the amendments. They were applied at a rate equivalent to 20 $kg\ P \cdot ha^{-1}$ based on the surface area of the pots. Amendments per pot were 0.16 g MAP, 15.6 g compost, 0.29 g struvite, 4.0 g frass, and 1.3 g digestate. The N:P ratios of the amendments varied, such that different amounts of N were supplied to each pot via the amendment treatments. The N addition from each amendment was equivalent to 9.4 $kg \cdot ha^{-1}$ for struvite, 73 $kg \cdot ha^{-1}$ for frass, 28 $kg \cdot ha^{-1}$ for digestate, 63 $kg \cdot ha^{-1}$ for compost, and 10 $kg \cdot ha^{-1}$ for MAP based on the surface area of the pots. The +N pots received 90 $kg \cdot N\ ha^{-1}$ as urea dissolved in 100 mL reverse osmosis water at the beginning of the experiment and after each biomass harvest to eliminate N deficiency. The −N pots received no nitrogen, but an equivalent amount of water. Based on the soil analysis, other nutrients were not expected to be limiting in this soil, and so no additional nutrient solution was added.

Pots were seeded with 25–30 Italian ryegrass seeds at an approximate depth of 0.5–1 cm and were later thinned to 10 plants per pot. Pots were watered by weight up to a target of 80% free-drained container water capacity using reverse osmosis water. Subsequently, pots were watered every 1–3 d. Approximately once per week, they were watered to their target weight and re-randomized within their blocks. Other waterings were done by weighing three to five randomly selected pots and watering based on the lower end of water use. Following the second biomass harvest (70 d after planting) +N and −N pots were watered separately due to substantially higher water use of the +N pots.

Fig. 1. Mean ryegrass dry matter biomass produced at four harvests 42, 70, 95, and 123 d after seeding (DAS). Six amendment treatments were included with or without nitrogen (N) addition. Bars with at least one letter in common are not significantly different based on repeated measures analysis using Tukey–Kramer means separation ($\alpha = 0.05$). MAP, mono-ammonium phosphate.



Pots were initially housed in a naturally lit greenhouse with ventilation but no cooling system, and experienced water stress on sunny days. After the first biomass harvest, pots were transferred to a naturally lit greenhouse with a cooling wall (mean temperature 19–23 °C), which alleviated water stress.

Sample collection and analysis

Four above-ground biomass harvests were conducted 42, 70, 95, and 123 d after seeding (DAS) (25–28 d between harvests) by cutting ryegrass plants just above the soil surface. Biomass was dried for a minimum of 48 h at 65 °C and weighed. Biomass samples were ground using a coffee grinder (Black and Decker, CBG100SC) for tissue P and Kjeldhal N determination. Sulfuric acid–peroxide wet-oxidation digestion was conducted on 0.4 g of each sample, and phosphorus was determined colorimetrically using the molybdate-blue ascorbic acid method, as described by Akinremi et al. (2003). Kjeldhal N in the digested samples was determined using a Technicon AutoAnalyzer II.

Statistical analysis

Two-way analysis of variance (ANOVA) was conducted using the GLIMMIX and MIXED ($\alpha = 0.05$) procedures of SAS software version 9.4, applying Tukey–Kramer means separation where the ANOVA results were significant (SAS Institute, Cary, NC, USA, 2017). Analysis of both cumulative and individual harvest date biomass, P uptake, and N uptake was performed; in the case of individual harvest dates, repeated measures analysis was used. Uniformity of variance was tested using COVTEST and comparison of Akaike information criterion values for different models, and non-homogeneous variance was incorporated into models as applicable using a Random_residual_/group statement. By default, PROC GLIMMIX was used, but in some cases, PROC GLIMMIX was unable to run when non-homogeneous variance was required. In these cases, PROC MIXED was used. Normality of residuals produced by the ANOVA was tested using PROC UNIVARIATE, with a threshold value of 0.9 for the Shapiro–Wilk's statistic. Assessment of normality for nitrogen uptake revealed two outliers at biomass harvest No. 2, a frass −N pot with very high N uptake and a MAP +N pot with very low nitrogen uptake. We concluded that their nitrogen applications had likely been switched, and they were removed from the analysis.

Results and Discussion

A significant ($p < 0.001$) amendment × nitrogen × harvest time effect was found for dry matter yield of ryegrass (Fig. 1). Yields at the first harvest date were significantly greater overall for the +N treatments, though the difference within amendment was not significant for any of the individual P source amendments. After the first harvest, biomass yields in the −N pots plummeted for all treatments, presumably due to N depletion. Biomass yields in the +N-amended pots remained steadily high or increased at subsequent harvests. In the +N pots, biomass yields were numerically higher for all treatments and statistically higher for struvite and frass compared with the control at harvest times 1 and 2. At the third and fourth harvests, all amended +N pots had statistically greater yield than the control.

Table 1. Average cumulative biomass yields, tissue phosphorus (P) uptake, and Kjeldhal nitrogen (N) uptake for ryegrass per pot.

		Cumulative biomass (g)	Cumulative tissue P (mg)	Cumulative tissue N (mg)
	+ Nitrogen	12.8 (0.2)a	18.3 (0.3)a	396 (4)a
	− Nitrogen	5.5 (0.1)b	16.8 (0.3)b	97 (0.6)b
	Control	6.6 (0.2)d	10.8 (0.3)e	180 (4)d
	Struvite	9.4 (0.2)bc	18.3 (0.3)c	243 (4)bc
	Digestate	8.9 (0.2)c	16.1 (0.3)d	236 (4)c
	Compost	9.2 (0.2)bc	17.5 (0.3)c	232 (4)c
	Frass	10.7 (0.2)a	23.0 (0.3)a	269 (4)a
	MAP	9.9 (0.2)b	19.5 (0.3)b	260 (5)ab
+ Nitrogen	Control	8.6 (0.3)c	10.0 (0.4)f	271 (8)d
	Struvite	13.4 (0.3)ab	19.5 (0.4)b	387 (8)abc
	Digestate	12.8 (0.3)b	17.3 (0.4)cd	379 (8)bc
	Compost	12.9 (0.3)b	18.3 (0.4)bc	367 (8)c
	Frass	14.8 (0.3)a	23.2 (0.4)a	426 (8)a
	MAP	14.1 (0.4)ab	21.6 (0.4)a	424 (10)ab
− Nitrogen	Control	4.7 (0.2)g	11.6 (0.4)f	89 (1.5)g
	Struvite	5.4 (0.2)ef	17.1 (0.4)cd	98 (1.3)f
	Digestate	5.1 (0.2)fg	15.0 (0.4)e	93 (1.3)fg
	Compost	5.5 (0.2)ef	16.7 (0.4)d	97 (1.3)f
	Frass	6.6 (0.2)d	22.8 (0.4)a	112 (1.5)e
	MAP	5.8 (0.2)e	17.3 (0.4)cd	97 (1.5)fg
ANOVA *p* values	Amendment	<0.0001	<0.0001	<0.0001
	Nitrogen	<0.0001	<0.0001	<0.0001
	Amd × Nit	<0.0001	<0.0001	<0.0001

Note: Treatment means within a column and effect (amendment, nitrogen, and amendment × nitrogen (Amd × Nit)) followed by the same lowercase letter are not significantly different based on Tukey–Kramer means separation ($\alpha = 0.05$). Standard error of the mean is given in brackets. MAP, mono-ammonium phosphate; ANOVA, analysis of variance.

Significant amendment, nitrogen, and amendment × nitrogen effects were found for cumulative biomass, P uptake, and N uptake (Table 1). All amendments significantly increased biomass yields in the +N pots. The increase was between 49% for digestate and 72% for frass. Frass yielded significantly more than the digestate and compost treatments, whereas MAP and struvite were statistically similar to all amended treatments. Phosphorus uptake was significantly increased in all +N amendments compared with the control, ranging from 70% with digestate to 130% with frass. Unlike biomass, where all amendments were not significantly different from MAP, only frass was not significantly different from MAP based on P uptake. Struvite and digestate had lower P uptake than MAP and were not significantly different from the compost comparison treatment. This aligns with previous studies that found solid food waste digestate had lower P availability than mineral fertilizers (Brod et al. 2015) and that struvite P availability is reduced compared with conventional fertilizers at high pH (Hertzberger et al. 2020). These results support our hypothesis that circular nutrient sources would increase P uptake and improve yields compared with a control in a P-depleted soil, when N was non-limiting.

In the −N pots, all amendments except digestate produced increased cumulative biomass (Table 1). Our secondary hypothesis was that high-N:P amendments would yield more than low-N:P amendments in N-limited conditions. The result for frass, which had the highest N:P ratio and the greatest N uptake and yield among the −N treatments appears to support the hypothesis. However, MAP and struvite, which had low N:P ratios, produced yield and N uptake not significantly different from compost, a high-N:P amendment. Digestate had an intermediate N:P ratio but produced yields and N uptake not significantly different from the control. The N in compost and digestate appears to be of low plant availability compared with that of frass. However, as non-limiting P was not supplied to the −N pots, we cannot conclusively determine whether yield differences were due to N supply; they may also be the result of P supply during early growth, before N was depleted.

Conclusions

All three recycled nutrient sources used in this study showed a capacity to supply P and substantially increase yields above an unamended control. In conditions of sufficient nitrogen, uptake of phosphorus was frass = MAP > struvite ≥ compost ≥ digestate >> control. Notably, all circular amendments produced biomass yields not significantly different from the soluble MAP fertilizer under greenhouse conditions for this ryegrass crop. Frass may also play an important role as an N source under N-limiting conditions. This research supports the role of these recycled materials as P sources. Further investigation and validation of these findings are needed under field conditions and with a variety of crop species on Prairie soils.

Acknowledgements

Jessica Nicksy was supported by the University of Manitoba Graduate Fellowship, and the Natural Sciences and Engineering Research Council of Canada CGS-M fellowship. The work was supported by the Organic Federation of Canada, the Organic Science Cluster III Program of Agriculture and Agrifood Canada, and Ostara Nutrient Recovery Technologies. We would also like to acknowledge Dr. Don Flaten for providing invaluable advice on greenhouse phosphorus amendment research, Joanne Thiessen-Martens for greenhouse help, Anthony Buckley for laboratory analysis assistance, Enterra Feed Corporation for providing the frass, and Ostara Nutrient Recovery Technologies Inc. for providing the struvite.

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