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ORIGINAL ARTICLE

Recycled nutrients supply phosphorus for organically-managed wheat and forage crops

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Abstract Recycling urban nutrients onto farmland has the potential to improve phosphorus (P) supply and yields on P-depleted organic farms, reduce global reliance on non-renewable mined phosphate rock, and reduce environmental contamination caused by excess P. Three recycled nutrient sources (struvite from municipal wastewater, frass from insect-processed food waste, and anaerobic digestate of food waste) were compared with common conventional (mono-ammonium phosphate, MAP) and organic (livestock compost) P sources in field experiments in spring wheat and forage hay on a high-pH (8.1–8.3) soil. Experiments were conducted on a low-P site (3 mg kg^{-1} Olsen P) over 2 years with conventional- and organically-selected wheat genotypes. In wheat, P uptake increased by 172%, 130%, 92%, and 43% compared to an unfertilized treatment for frass, MAP, compost, and digestate, respectively. Frass, MAP, compost and digestate increased grain yield by 41%, 40%, 29%, and 20%, respectively. Struvite did not significantly increase yields or P uptake. For both P uptake and grain yield, frass and compost treatments were similar to the "conventional" MAP treatment, while digestate and struvite treatments were lower than MAP. An organically-selected wheat genotype produced greater biomass but similar yield compared to a conventional genotype, demonstrating some genotype advantage. In the forage-hay crop, cumulative P uptake increased by 124%, 99%, 86%, 73%, and 65% compared to an unfertilized treatment for frass, MAP, digestate, struvite, and compost, respectively. Yield increased only in the second year of the trial, by 136%, 125%, 112%, 94%, and 79% for frass, struvite, MAP, digestate, and compost, respectively. The recycled nutrient sources varied in their efficacy in the two crops and relative to other nutrient sources, but all showed some potential to supply P and improve yields on a P-depleted soil.

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Introduction

Organically-managed agricultural cropping systems can experience nutrient deficiency and system collapse over the long term, particularly caused by phosphorus (P) depletion (Welsh et al. 2009). Phosphorus depletion from plant-available pools, due to greater P exports compared to inputs, is common on many organically-managed farms (Entz et al. 2001; Gosling and Shepherd 2005; Welsh et al. 2009; Knight et al. 2010; Reimer et al. 2020). It is a non-renewable resource, with estimates for minable phosphate rock depletion in as little as 70–140 years (Li et al. 2018). Jarvie et al. (2015) demonstrate P's important and paradoxical role in the food–energy–water nexus, as a necessary resource for food and biofuel production, but as a harmful contaminant in aquatic ecosystems, causing eutrophication when present in excess. Diverting more food and human waste products to farms via recycled nutrient sources, rather than allowing them to enter landfills or waterways, could ameliorate P deficiency on organic farms, depletion of the phosphate rock resource, and damage to aquatic ecosystems due to P-enhanced eutrophication.

Recycled nutrient sources have received increasing attention and are part of the European Union's action plan for a "Circular Economy" (European Commision 2015), with many recent publications focusing on incorporating food and human wastes into the circular economy (e.g., Kibler et al. 2018; Ma and Liu 2019; Case and Jensen 2019). However, the literature addressing the agronomic potential and P characterization of recycled nutrients lags behind that dealing with conventional fertilizer and manure sources (Nicksy and Entz 2021). Recycled nutrient sources of urban origin used to increase P availability to crop plants may be of human, food, or yard waste origin. While this study focuses on human-waste-derived struvite, and food-waste-derived insect frass and anaerobic digestate, other urban nutrient sources are many and varied, including biosolids, municipal food waste composts, sewage sludge ashes, and precipitated minerals other than struvite (Hargreaves et al. 2008; Möller et al. 2018; Schneider et al. 2019).

Struvite is a hydrated magnesium–ammonium–phosphate mineral, which can be generated from human- or animal-waste waters. It is precipitated under alkaline conditions, and has greater solubility with decreasing pH (Bhuiyan et al. 2007). Degryse et al. (2017) showed that high-pH soils had dissolution rates of less than 1/8 those of acidic soils. A meta-analysis found that the crop response to struvite decreased relative to ammonium phosphates and superphosphates with increasing pH in both field and pot experiments, with response ratios (struvite response relative to reference fertilizer response) greater than 1 in acidic soils and less than 1 in alkaline soils (Hertzberger et al. 2020). However, a pot experiment using high-pH soil from the same field site used in the present study found similar Italian ryegrass (*Lolium multiflorum*) yields from struvite and mono-ammonium phosphate (MAP), though cumulative P uptake was slightly lower for struvite (Nicksy et al. 2021).

Frass is the waste product of insects, analogous to insect "manure". Black-soldier-fly larvae (*Hermetia illucens*) in particular are effective processors of organic waste, including urban food waste, with the ability to feed on a wide variety of organic materials (Čičková et al. 2015). Research into biodegradation of organic wastes by insect larvae has generally focussed on production of larval biomass for livestock and pet foods, whereas insect frass is poorly studied as a soil amendment. A pot study we conducted on a high-pH clay soil revealed similar yields and P uptake of frass compared to MAP (Nicksy et al. 2021). Other studies have evaluated frass on a nitrogen (N) basis or as a component of a potting medium. Kebli and Sinaj (2017) found that frass from food waste consistently improved yields in a pot study on three soils from Switzerland using lettuce and ryegrass. However, it was only in a sandy, low-pH soil that yields were similar to or greater than the mineral fertilizer. Setti et al. (2019) evaluated black-soldier-fly processing residue (frass and bedding) mixed with peat moss as a greenhouse growing medium at rates between 10 and 40% by volume. High rates of frass reduced emergence in lettuce, basil, and tomato, and the best yields were generally found for 10% frass:90% peat moss and for 100% peat moss with mineral fertilizer.

Anaerobic digestion is the process of decomposing organic material in the absence of oxygen. The digestion produces methane biogas, which can be used directly in electricity and heat generation, or upgraded as a vehicle fuel or injected into natural gas lines (Wainaina et al. 2020). Liquid and solid fractions of digestate can be applied together or separately, with solid fractions tending to have higher P concentrations than liquid (Nkoa 2014). Phosphorus characterization of food-waste digestate is limited, but Brod et al. (2015) found a higher proportion of chemically-recalcitrant species, and especially Ca-associated phosphates, in solid compared to liquid digestate. The solid digestate had lower P recovery in their pot experiment compared to liquid digestate and mineral fertilizer in both acidic (pH 5.5) and near-neutral (pH 6.9) soils. Phosphorus recovery from several recycled nutrient sources was negatively related to the acid-soluble Ca-associated fraction of P in the near-neutral soil. Nicksy et al. (2021) found similar yield but lower P uptake from solid dried and pelletized digestate compared to mineral fertilizer in a pot study.

Plant access to P depends not only on amendment and soil properties, but also varies widely among plant species (Strong and Soper 1974). Further, genotypic differences among varieties within a species can result in differences in P uptake from the same soil (Clark 1983). Recently, efforts have begun to breed grains destined for use on organic farms under organic rather than conventional management practices (Entz et al. 2018); these breeding efforts may result in different genotypes varying in their ability to access soil or amendment P.

Here, we investigate the agronomic potential, and especially the P-supplying capacity, of struvite, frass, and digestate on spring wheat (*Triticum aestivum*) and forage crops grown on a high-pH, P-depleted soil. These are compared to common P sources used in both conventional (MAP) and organically-managed (compost) agriculture. P content and availability of organic wastes varies widely with substrate source and processing (Sharpley and Moyer 2000), but composted organic waste usually has good P availability compared to synthetic fertilizers (Sikora and Enkiri 2005; Zvomuya et al. 2006; Ramphisa et al. 2020).

We hypothesized that the recycled nutrient sources would increase P uptake and crop yields compared to an unfertilized control, and that they would be similarly effective compared to a conventional MAP fertilizer and an organic compost; further, recycled nutrients would supply P to crops equally well in annual wheat and perennial forage cropping systems. We also hypothesized that a wheat genotype selected under low-P organic conditions would out-perform a conventionally-selected genotype on a low-P soil.

Methods

Soil amendments

The struvite was precipitated from municipal wastewater and had a median granule size of 3 mm. The frass is the waste product of black-soldier-fly larvae used to process urban food waste. The anaerobic digestate was industrially produced through the decomposition of food retail and processing waste in the absence of oxygen. The P source typical of organic agriculture was aerobically-composted organic wastes, with horse manure and bedding as the primary substrates, along with shredded wood and bark, hatchery waste, yard waste, and waste protein powder. The conventional P source was a soluble synthetic fertilizer, MAP.

Properties of frass, digestate, and compost were determined by Agvise Laboratories, ND, USA; the N and P content of the mineral struvite and MAP were based on manufacturer specifications (Table S1). The P content varied by two orders of magnitude, with the organic-matter amendments (frass, digestate, compost) containing less P than the mineral amendments (MAP, struvite) by mass. Within the organic-matter amendments, digestate contained approximately 12 times (27.5 g kg^{-1}), and frass contained almost 4 times (8.74 g kg^{-1}), the P contained in compost (2.27 g kg^{-1}). Struvite (120 g kg^{-1}) contained approximately half the P of MAP (230 g kg^{-1}). The amendments also varied in N content and N:P ratio, with frass and compost having the greatest N:P, struvite and MAP having very low N:P, and digestate having intermediate N:P. All amendments were applied based on a total-P rate of 20 kg ha^{-1} P, resulting in varied rates of N addition of 73, 28, 63, 8.3, and 9.6 kg ha^{-1} for frass, digestate, compost, struvite, and MAP, respectively. Total amendment application rates to meet 20 kg ha^{-1} P were 2290, 726, 8800, 163, and 88 kg ha^{-1} for frass, digestate, compost, struvite, and MAP, respectively.

Field site

The experiments were conducted in 2019 and 2020 at an organically-managed field site in the North-American Great Plains near Libau, MB, Canada (50°24′01″ N, 96°72′95″ W), which has a cool-subhumid-continental climate. The soil is a Gleyed-Rego-Black

Chernozem with a clay texture. Spring soil tests, composited from 5 samples taken across the study areas, (Agvise Laboratories, ND, USA) showed that all fields had very low Olsen-P concentrations of 2–3 mg kg^{-1} soil (Table S2), because forage hay had been harvested since 2006 with no added nutrients. Normal growing-season rainfall is about 250 mm in this area: 2019 was extremely dry, with only 40% of the long-term normal, whereas 2020 had about 80% of the normal (Table S3).

Wheat experiment

In 2017 the wheat experiment areas were converted from forage to annual cropping. Legume-cereal green manures were grown in the year prior to the wheat experiments to fix and supply N to the wheat crop, which is typical of organic management practices for the region. The 2018 green manure was terminated and incorporated in the fall of 2018 prior to the 2019 wheat experiment. Heavy fall rains prevented incorporation of the 2019 green manure until the spring of 2020, causing soil clodding and poor seedbed quality. Spring incorporation of green manures may account for the lower nitrate values in 2020, as the green manure had not had time to mineralize.

A randomized-complete-block design with four replicates was used for the wheat experiments in 2019 and 2020. The treatment layout was fully factorial with amendment (struvite, frass, digestate, MAP, compost, unfertilized control) and wheat genotype (AAC Brandon and BJ08-IG) as the two factors. AAC Brandon is conventionally bred and is the most popular wheat variety in Manitoba by area planted (Manitoba Agricultural Services Corporation 2018). BJ08-IG is a genotype selected through a partnership between professional plant breeders and organic farmers (Entz et al. 2018). BJ08-IG was selected by a farmer under low-P conditions. It produces taller plants with greater biomass and similar days to maturity as AAC Brandon, as well as greater yields in 2 of 3 years (Entz et al. 2018).

Fields were tilled with a light-duty cultivator (2019) or a heavy-duty followed by a light-duty cultivator (2020) depending on field conditions, within 5 d prior to seeding. Amendments were broadcast by hand into 2 m × 10 m plots and incorporated with a rototiller to 0.1 m immediately prior to planting. Wheat was planted May 16 in 2019 and May 29 in 2020 at a target depth of 0.05 m with 0.15-m-row spacing using a plot seeder equipped with a seed distribution cone (Fabro Industries, Swift Current, SK, Canada). In 2019 a target seeding rate of 350 plants m^{-2} was used. In 2020 the target seeding rate was increased to 450 plants m^{-2} to compensate for poor seedbed quality.

A 0.3 m^2 (2 rows × 1 m) biomass sample was taken at stem elongation and anthesis on June 27 and July 16 in 2019 and July 2 and July 16 in 2020. A 0.9 m^2 (6 rows × 1 m) biomass sample was taken at physiological maturity on August 7 in 2019 and August 24 in 2020. Biomass samples were oven-dried at 65 °C for a minimum of 48 h before weighing. Wheat grain was harvested on August 23 in 2019 using a Wintersteiger plot combine (Wintersteiger Model "Classic", Saskatoon, Canada) and on September 10 in 2020 using a Hege plot combine (Hege model 125, Hege Company, Waldenburg, Germany). Grain samples were air dried on forced-air beds for 72 h before weighing.

Forage experiment

The forage trial was established on a 13-years-old forage hay stand. Prior to the experiment, hay was usually harvested 1–2 times per year, and no external nutrient addition occurred during this period. Another experiment conducted on the same forage stand concluded that alfalfa (*Medicago sativa*) composed 34–76% of the stand by biomass, with plots receiving higher rates of P fertility having a greater proportion of alfalfa (Thiessen Martens et al. 2021). Alfalfa and grass were not separated in the present experiment, though visual inspection indicated that fertilized plots likely had a greater proportion of alfalfa biomass compared to unfertilized plots. Grass species included orchardgrass (*Dactilus glomerata* L.), meadow bromegrass (*Bromus biebersteinii*) and quackgrass (*Elymus repens*).

A one-factor randomized-complete-block design with four replicates and 2 m × 10 m plots was used for the forage experiment with all six amendments. All amendments except struvite were surface broadcast on May 16 and 17 of 2019. Struvite was subsurface banded at a depth of 0.05 m using the Fabro seeder on May 16 due to its low solubility. Four biomass samples were taken through the two growing seasons to roughly correspond with farmer hay harvests. The first 2019 biomass sample used a hand sickle, but all subsequent sampling used two passes of a 0.5 m wide push mower with a bag attachment to increase the sample area. The wet biomass from each plot was weighed, mixed to homogenize, subsampled, and oven-dried at 65 °C for 48 h to determine dry biomass.

P and N determination

Biomass samples were ground using a Wiley mill with a 2-mm mesh, and wheat-grain samples were ground using a Cyclone sample mill with a 1-mm mesh. A 0.4 g subsample was hot-digested using a sulfuric acid-hydrogen peroxide solution, and P was determined colorimetrically using the molybdate-blue ascorbic-acid method (Akinremi et al. (2003). Kjeldahl N of the digested samples was determined on a Technicon Autoanalyzer II. Wheat-grain protein content was estimated by multiplying Kjeldahl-N content by 5.7 (McDonald 1977). P and N uptake were calculated by multiplying nutrient concentration by yield. P recovery in grain (wheat) and biomass (forage) was calculated as the difference between the uptake for each amendment and the unfertilized control, expressed as a percentage of the P applied.

Statistical analysis

Analysis of variance (ANOVA) for yield, nutrient content, and nutrient recovery was conducted using PROC GLIMMIX in SAS software (SAS Institute, 2017, version 9.4). For the wheat experiments, amendment, genotype, and amendment × genotype were fixed effects, and block (year) and year were random effects. Each sampling time was analysed independently. For forage, amendment was a fixed effect and block was a random effect. Forage-response variables were assessed separately at each harvest, as well as summed by year and summed over both years for yield and P recovery. Normality of residuals was tested with PROC UNIVARIATE, with Shapiro–Wilk values of greater than 0.9 indicating near-normal data. Homogeneity of variance was tested by comparing Akaike Information Criterion (AIC) values of models with and without heterogenous variance; heterogenous variance was included in the model when it produced the lowest AIC. ANOVA for P recovery as a percentage of applied P was determined using a beta distribution.

Relationships between tissue nutrient concentration at each sampling time and grain or biomass yield were calculated as a simple-linear function (modelled using lm in base R version 4.1.1) compared to a linear-plateau function (modelled using nlsLM in the minpack.lm package). The model with the higher adjusted r^2 value (r^2 corrected for number of parameters used in the model) was selected if $p > 0.05$ for both. Separate models were performed for each year because samples were at slightly different days after planting between years. ANOVA of seedling emergence was conducted separately for each year.

Results

Wheat

Amendment effect on biomass and phosphorus uptake

There was no effect of amendment on seedling emergence or plant density in either year (2019 mean = 321 and 2020 mean = 287 plants m^{-2}). All amendments except struvite produced greater biomass and grain yields compared to the unfertilized control at every sampling time (Table 1). Digestate biomass and grain yield were similar to the organic "business as usual" compost treatment at anthesis, maturity, and grain harvest, but was lower at stem elongation. The digestate treatment always yielded less than the conventional "business as usual" MAP treatment. The frass treatment produced greater early-season stem elongation biomass than compost, and similar biomass/grain yield at subsequent samplings. Frass was the only amendment that consistently produced similar yields to the conventional MAP treatment. Frass consistently produced higher tissue-P concentrations than all other amendments, and greater P uptake than all amendments except MAP (Table 2). Digestate produced greater tissue P and uptake than the unfertilized control, and was similar to compost at all times after stem elongation. Struvite had similar tissue-P concentrations and P uptake compared to the control. P recovery was affected by amendment at stem elongation, anthesis, and grain harvest. The performance of the amendments relative to each other was fairly

Table 1 Mean wheat yield over 2 years for genotype and amendment treatments

	Biomass yield, kg ha^{-1}									Wheat grain, kg ha^{-1}		
	Stem elongation			Anthesis			Maturity			Harvest		
Genotype												
AAC Brandon	840	(110)	B	2930	(110)	B	5310	(290)	B	2590	(480)	
BJ08-IG	940	(110)	A	3200	(110)	A	5670	(290)	A	2600	(480)	
Amendment												
Unfertilized	620	(110)	D	2410	(140)	E	4550	(310)	D	2100	(480)	D
Struvite	730	(110)	CD	2700	(140)	DE	5030	(310)	CD	2340	(480)	CD
Digestate	770	(110)	C	2880	(140)	CD	5350	(310)	BC	2520	(480)	BC
Compost	980	(110)	B	3170	(140)	BC	5780	(310)	AB	2710	(480)	AB
Frass	1120	(110)	A	3470	(140)	AB	6090	(310)	A	2950	(480)	A
MAP*	1100	(110)	AB	3750	(140)	A	6140	(310)	A	2940	(480)	A
p value												
Genotype	0.0004			0.0021			0.0009			0.85		
Amendment	< 0.0001			< 0.0001			< 0.0001			< 0.0001		
Geno*Amd	0.01			0.39			0.57			0.39		

Standard error of the mean is given in brackets. Means followed by the same letter, within the same column and factor, are not significantly different based on the Tukey multiple comparison procedure at an alpha of 0.05

MAP mono-ammonium phosphate

consistent at each sampling time (Fig. 1). P recovery in grain ranged from 5 to 22%; frass and MAP recovery were greatest, whereas struvite and digestate were lowest.

Genotype effect

Seedling emergence and plant density were independent of genotype in 2019, but BJ08-IG had a greater plant density in 2020 (302 plants m^{-2} for BJ08-IG; 271 plants m^{-2} for AAC Brandon). BJ08-IG produced similar grain yield to AAC Brandon, but greater biomass at all biomass sampling times (Table 1) indicating greater straw production by BJ08-IG. BJ08-IG was also taller (0.81 m, CV 6%) than AAC Brandon (0.64 m, CV 7%) at physiological maturity. The genotype effect on P recovery was at anthesis only, where BJ08-IG (11% recovery) had a 49% greater P recovery than Brandon (7.4% recovery). A genotype by amendment effect on biomass was found at stem elongation only ($p = 0.01$), but the moderately conservative Tukey multiple comparison procedure found no differences between the varieties within the same amendment. This genotype by amendment interaction did not persist later in the season.

Attribution of yield differences to nutrient supply

We investigated the importance of P nutrition in driving yields by modelling linear or linear-plateau relationships between tissue-P concentration and grain yields (Fig. 2). P supply is adequate and not limiting if a plateau is reached. Positive relationships between tissue-P and grain yield were observed at stem elongation, anthesis, and harvest in 2019, and at stem elongation and anthesis in 2020. The relationships were marginally better using linear-plateau models than simple-linear models at four of five sampling times with significant relationships, suggesting sufficient P at higher tissue concentrations.

We also tested whether differences in N supplied by the amendments contributed to yield differences by regressing the N-tissue concentration (converted to % protein for grain) and the biomass yield. Lower N-tissue concentration was consistently associated with higher yields, indicating dilution of N ($p < 0.001$ at harvest in both 2019 and 2020). The negative relationship between yield and N concentration is also evident in the amendment effect on grain protein (Fig. 3). Treatments which produced the greatest yields (frass, MAP, compost) had lower protein content than the lower-yielding treatments (unfertilized,

Table 2 Mean wheat tissue P and P uptake over 2 years by genotype and amendment treatments

	Stem elongation						Anthesis						Grain yield					
	Tissue P, g kg^{-1}			P uptake, kg ha^{-1}			Tissue P, g kg^{-1}			P uptake, kg ha^{-1}			Tissue P, g kg^{-1}			P uptake, kg ha^{-1}		
Brandon	2.2	(0.4)	A	1.8	(0.2)		1.5	(0.2)		4.4	(0.7)	B	3.2	(0.2)	B	8.4	(2.2)	B
BJ08-IG	1.9	(0.4)	B	1.8	(0.2)		1.5	(0.2)		4.7	(0.7)	A	3.4	(0.2)	A	8.9	(2.2)	A
Unfertilized	1.7	(0.4)	D	1.0	(0.2)	D	1.3	(0.2)	C	3.0	(0.7)	D	2.9	(0.2)	C	6.3	(2.2)	D
Struvite	1.9	(0.4)	CD	1.3	(0.2)	CD	1.4	(0.2)	BC	3.7	(0.7)	CD	3.1	(0.2)	C	7.3	(2.2)	D
Digestate	2.0	(0.4)	BC	1.5	(0.2)	C	1.5	(0.2)	B	4.2	(0.7)	BC	3.3	(0.2)	B	8.4	(2.2)	C
Compost	2.1	(0.4)	BC	2.0	(0.2)	B	1.5	(0.2)	B	4.6	(0.7)	B	3.3	(0.2)	B	9.1	(2.2)	BC
Frass	2.5	(0.4)	A	2.8	(0.2)	A	1.8	(0.2)	A	6.1	(0.7)	A	3.6	(0.2)	A	10.7	(2.2)	A
MAP*	2.2	(0.4)	B	2.3	(0.2)	AB	1.5	(0.2)	B	5.6	(0.7)	A	3.3	(0.2)	B	9.9	(2.2)	AB
p value																		
Genotype	< 0.0001			0.92			0.39			0.03			< 0.0001			0.0134		
Amendment	< 0.0001			< 0.0001			< 0.0001			< 0.0001			< 0.0001			< 0.0001		
Geno*Amd	0.93			0.13			0.36			0.06			0.62			0.1634		

Means followed by the same letter, within the same column and factor, are not significantly different based on the Tukey multiple comparison procedure at an alpha of 0.05

MAP mono-ammonium phosphate

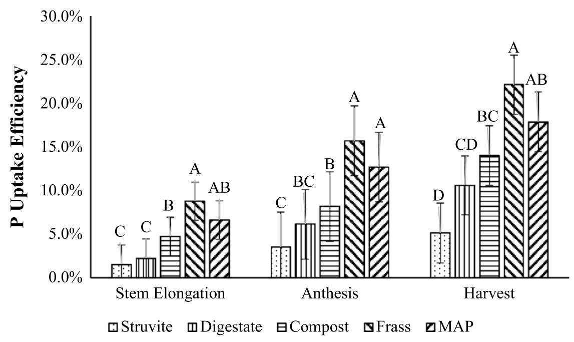

Fig. 1 Phosphorus recovery of each amendment (mean of two genotypes) in wheat grain, based on 20 kg ha^{-1} applied P. Error bars are standard error. Treatments at the same sampling time with the same letter are not significantly different based on the Tukey multiple comparison procedure at an alpha of 0.05. *MAP* mono-ammonium phosphate

struvite, digestate), consistent with a dilution effect at greater yields. Low grain yield is commonly associated with high grain N concentration when yield is limited by another factor (Woodard and Bly 1998), in this case P deficiency. There was no relationship between N addition of amendments and mean yield ($p = 0.61$). Thus, N applied in the amendments did not appear to impact yield differences, though it is impossible to conclude no N effect with certainty without compensating for N additions using soluble N fertilizer. Given the goal of this experiment to evaluate the amendments in an organic cropping system, this was outside the scope of the project.

Perennial forage

Amendment effect on biomass and phosphorus uptake

There was no effect of amendment on the forage production in 2019, but there was at both harvest times in 2020 (Table 3). Tissue-P concentration and P uptake were affected by amendment at every sampling time (Table 4). At the first biomass sample on July 14, 2019, struvite and frass had greater tissue-P concentration than the unfertilized control, and frass also had greater P uptake than the control. By the second biomass sample on August 20, 2019, all amendments had greater tissue-P concentration than the control, and frass and MAP had greater tissue P than compost, digestate, and struvite. Only frass and MAP demonstrated greater total P uptake than the control. At the third biomass sample on

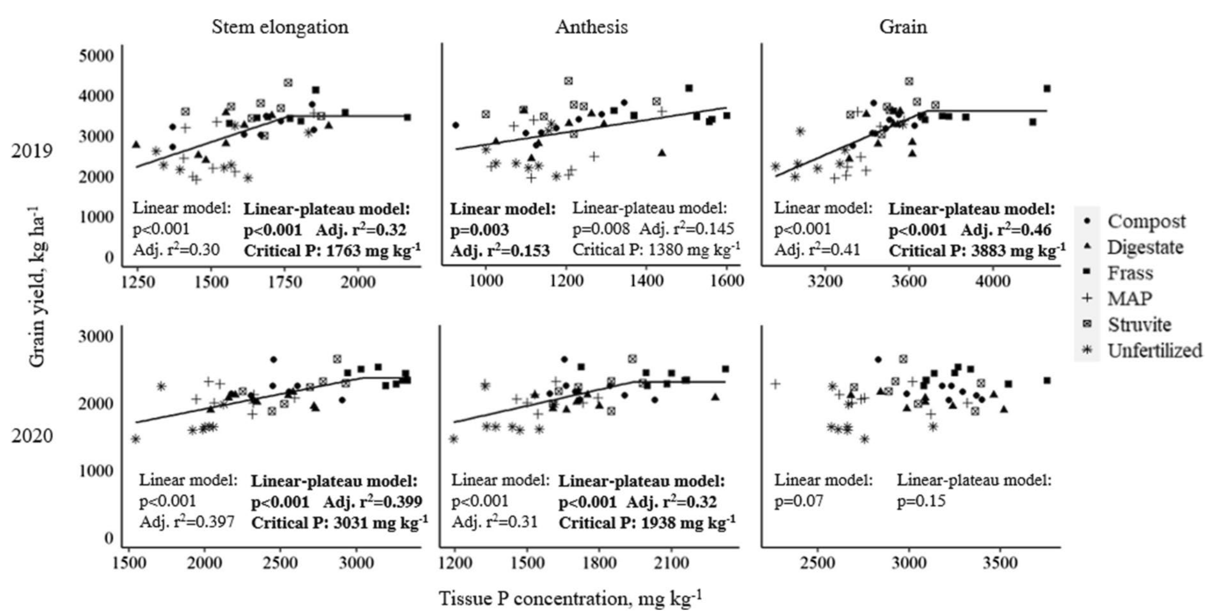

Fig. 2 Relationships between final wheat grain yield and grain/tissue P concentration in 2019 and 2020 (both genotypes). The choice of model (linear or linear-plateau) is based on adjusted r^2 value, and the line of the chosen model is plotted on the graph. Where the model is not significant, as indicated by a p value > 0.05 no line is plotted. *MAP* mono-ammonium phosphate

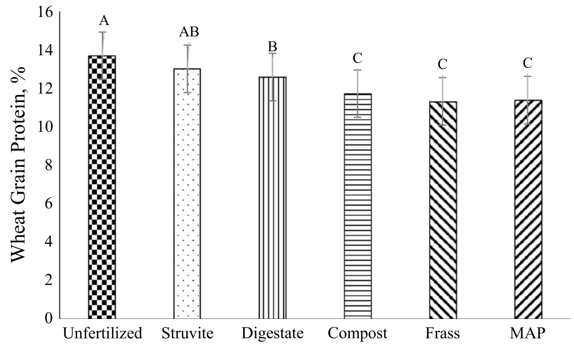

Fig. 3 Wheat grain protein content by amendment treatment. Error bars are standard error of the mean. Treatments with the same letter are not significantly different based on the Tukey multiple comparison procedure at an alpha of 0.05. *MAP* mono-ammonium phosphate

June 21, 2020, all amendments had greater biomass, tissue P, and P uptake than the control, except for the compost. At the final biomass sample, all amendments except compost had greater biomass and P uptake than the control, while all amendments except digestate and compost had greater tissue P than the control. All amendments increased biomass production compared to the control when both 2020 harvests were summed. Yield increases compared to the control were 137% for frass, 126% for struvite, 113% for MAP, 95% for digestate, and 79% for compost.

Attribution of yield differences to nutrient supply

We evaluated P nutrition as a driving factor in forage biomass production by modelling linear- and linear-plateau relationships between tissue-P concentration and yield (Fig. 4). Linear-plateau models were better than simple-linear models for both harvests in 2020, indicating that some plots were P sufficient. In 2019 there was no relationship between biomass yield and tissue-P concentration at either sampling date. There was no relationship between biomass production and tissue-N concentration at any sampling time. All amendments except compost increased total-N uptake in 2020 (Fig. 5).

Discussion

Relative performance of recycled nutrients varies between crops

Our hypothesis that recycled nutrient sources would supply P and improve yields compared to an unamended control, and that they would perform similarly compared to organic (compost) and conventional (MAP) comparison treatments, was upheld for all three recycled nutrient sources in forage hay, but was only true for frass in the wheat experiment.

Struvite did not increase wheat yield or tissue P compared to the unfertilized control. However, at this field site, Thiessen-Martens et al. (2021) showed an increase in spring-wheat yield with increasing

Table 3 Forage dry biomass harvested

	Harvest dates										Cumulative biomass		
	14-Jul-19		20-Aug-19		21-Jun-20			28-Jul-20					
	kg ha^{-1}												
Unfertilized	880	(120)	1180	(130)	390	(80)	C	440	(90)	B	2900	(360)	B
Struvite	910	(120)	1260	(130)	1000	(80)	AB	760	(90)	A	4050	(360)	AB
Digestate	1100	(120)	1420	(130)	870	(80)	AB	890	(90)	A	4150	(360)	A
Compost	1140	(120)	1250	(130)	850	(80)	B	650	(90)	AB	3890	(360)	AB
Frass	1290	(120)	1320	(130)	1100	(80)	A	880	(90)	A	4590	(360)	A
MAP*	1020	(120)	1290	(130)	910	(80)	AB	870	(90)	A	4100	(360)	AB
ANOVA *p* value	0.12		0.67		< 0.0001			0.0008			0.01		

Standard error of the mean is given in brackets. Values in the same column followed by the same letter are not significantly different based on the Tukey multiple comparison procedure at an alpha of 0.05

MAP mono-ammonium phosphate

Table 4 Phosphorus tissue and uptake values for forage, and cumulative P uptake and recovery efficiency based on 20 kg ha^{-1} P applied

	14-Jul-19						20-Aug-19						21-Jun-20					
	Tissue P, g kg^{-1}			P uptake, kg ha^{-1}			Tissue P, g kg^{-1}			P uptake, kg ha^{-1}			Tissue P, g kg^{-1}			P uptake, kg ha^{-1}		
Unfertilized	0.75	(0.47)	B	0.66	(0.12)	B	0.73	(0.35)	C	0.86	(0.13)	B	1.11	(0.53)	C	0.44	(0.13)	C
Struvite	0.92	(0.47)	A	0.82	(0.12)	AB	0.92	(0.35)	B	1.15	(0.13)	AB	1.46	(0.53)	AB	1.46	(0.13)	AB
Digestate	0.83	(0.47)	AB	0.92	(0.12)	AB	0.88	(0.35)	B	1.26	(0.13)	AB	1.33	(0.53)	B	1.17	(0.13)	B
Compost	0.83	(0.47)	AB	0.95	(0.12)	AB	0.91	(0.35)	B	1.15	(0.13)	AB	1.34	(0.53)	B	1.14	(0.13)	B
Frass	0.97	(0.47)	A	1.25	(0.12)	A	1.10	(0.35)	A	1.47	(0.13)	A	1.49	(0.53)	A	1.64	(0.13)	A
MAP*	0.91	(0.47)	AB	0.93	(0.12)	AB	1.08	(0.35)	A	1.40	(0.13)	A	1.58	(0.53)	A	1.44	(0.13)	AB
ANOVA *p* value	0.0076			0.0255			< 0.0001			0.0046			< 0.0001			< 0.0001		

	28-Jul-20						Cumulative				
	Tissue P, g kg^{-1}			P uptake, kg ha^{-1}			P uptake, kg ha^{-1}			Recovery (%)	
Unfertilized	0.96	(0.35)	B	0.43	(0.10)	C	2.39	(0.42)	C	–	
Struvite	1.15	(0.35)	A	1.01	(0.10)	A	4.45	(0.42)	AB	10.3%	AB
Digestate	1.05	(0.35)	AB	0.79	(0.10)	AB	4.14	(0.42)	AB	8.7%	B
Compost	1.06	(0.35)	AB	0.69	(0.10)	BC	3.93	(0.42)	B	7.7%	B
Frass	1.13	(0.35)	A	0.99	(0.10)	AB	5.35	(0.42)	A	14.8%	A
MAP*	1.15	(0.35)	A	1.00	(0.10)	AB	4.76	(0.42)	AB	11.9%	AB
ANOVA *p* value	0.0023			0.0001			< 0.0001			0.014	

Standard error of the mean is given in brackets. Values in the same column followed by the same letter are not significantly different based on the Tukey multiple comparison procedure at an alpha of 0.05

MAP mono-ammonium phosphate

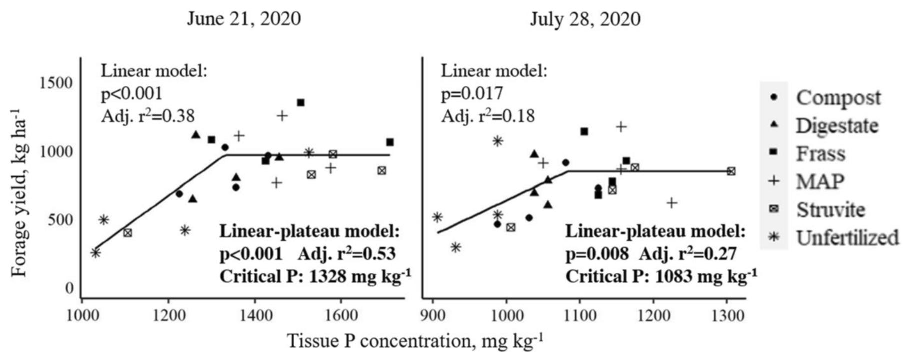

Fig. 4 Relationships between forage biomass produced and tissue phosphorus content for the two 2020 harvest dates. Linear plateau models had greater adjusted r^2 values for both time points. *MAP* mono-ammonium phosphate

struvite application at rates from 20 to 40 kg P ha^{-1}. They banded the struvite into the seed row, which may have increased the availability. While we are unaware of experiments directly comparing banded versus broadcast struvite, banding conventional P fertilizers improves their efficiency compared to broadcast (Grant and Flaten 2019), so banding of struvite may enhance wheat access, particularly in high-pH soils where dissolution is much lower than in acidic soils (Degryse et al. 2017). By contrast, struvite increased tissue-P concentration in the forage experiment from the first sampling time, possibly because struvite was banded into the forage and was immediately in the root zone, while the other amendments were surface broadcast. Many plants can concentrate root growth in locations of high soil P (Strong and Soper 1974; Rose et al. 2009), which may improve P acquisition of banded struvite compared to a diffuse source. Struvite performed similarly to other nutrient sources, including the conventional MAP and organic compost "business as usual" comparisons, in increasing P uptake and forage yield in 2020. Overall, struvite underperformed compared to other nutrient sources in wheat, but was similar to other nutrient sources in the forage system.

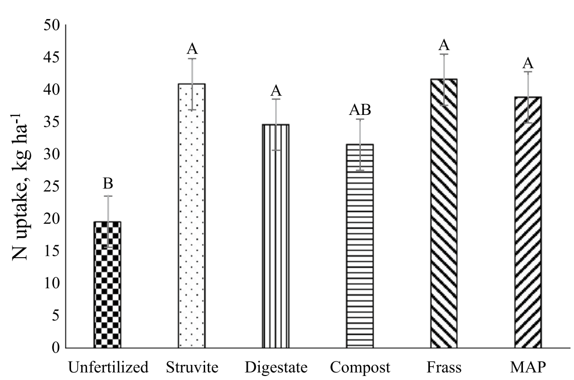

Fig. 5 Cumulative nitrogen uptake by forage for 2020. Bars with the same letter are not significantly different based on the Tukey multiple comparison procedure at an alpha of 0.05. *MAP* mono-ammonium phosphate

The lower yield response and P uptake of wheat by digestate compared to compost (at stem elongation only), frass, and MAP could be explained by a high proportion of the P existing in the less-soluble fractions which wheat cannot easily access. Brod et al. (2015) characterized liquid and solid food-waste digestate, based on a modified Hedley fractionation, XRD, and ^{31}P MAS_NMR. Only 22% of the solid digestate fraction P was H_2O or $NaHCO_3$ extractable, compared to 38% in the liquid digestate. The solid digestate had a particularly high proportion of acid (HCl)-soluble recalcitrant P, which may be less available in high soil pH. This led to lower P uptake of the solid digestate compared to the liquid digestate in the associated ryegrass pot study (Brod et al. 2015). Thus, the relatively low P availability of the digestate in our field study may be attributable to the use of the solid, rather than liquid, fraction of the digestate, though we did not perform any fractionations on our digestate to confirm this. However, Bachmann et al. (2016) found that the soluble fraction of P based on Hedley fractionation did not differ among liquid, solid, and solid-dried fractions of dairy slurry/maize silage and mixed-crop-silage digestates. Further work is needed to determine whether food waste is consistent in having less available P in its solid fraction, or whether this property is simply variable among all digestates. In forage, frass and digestate were the only nutrient sources to increase cumulative biomass over both years. This suggests that the forage was able to adequately access the P in the digestate, regardless of its potentially low solubility. Overall, digestate slightly underperformed compared to "business as usual" compost and MAP in wheat, but performed similarly or better in the forage experiment.

The similarity between frass and MAP in terms of wheat biomass/grain yield and P uptake at all sampling times indicates similar P availability to the wheat plant, at least over a single growing season. This is consistent with the findings of our previous pot study, where P uptake and ryegrass yields were similar between frass and MAP treatments (Nicksy et al. 2021). However, little work has been done on P-supplying properties of food-waste-derived frass in other soils and climates, highlighting the need to better characterize the P-supplying potential of frass. Both frass and struvite increased the P concentration in the forage tissue at the earliest biomass sample, indicating rapid access to these amendments. However, struvite was banded directly into the root zone, whereas frass was surface applied. The frass P must have dissolved and infiltrated the soil in rainwater to be available to plant roots. There was only 34 mm of rainfall between amendment application on May 16/17 and the initial biomass samples on July 14, with only one rainfall event greater than 10 mm, suggesting rapid solubility and plant availability of P in frass. Across both experiments, frass consistently produced yields and P uptake similar to or greater than the conventional MAP, and generally greater than organic compost, suggesting that P in frass is highly accessible to crop plants.

Ideally, we would have detailed information on all chemical forms of P in each amendment and how P behaves in the soil environment throughout the growing season. The chemistry of MAP is well known, but organic amendments are highly variable and complex to characterize (e.g., Sharpley and Moyer 2000; Frossard et al. 2002; Gagnon et al. 2012). Our use of plant response to the amendments is the most direct indicator of efficacy, although characterization of chemical species under different environments and agronomic practices is an important future step.

Wheat genotype impacts early season P uptake

The farmer-selected line, BJ08-IG, had higher P concentration and uptake in the grain compared to conventionally-bred AAC Brandon. BJ08-IG also had greater straw yield despite similar grain yield. Greater P acquisition by BJ08-IG may have helped to promote higher biomass yields. However, a high concentration of P in grain is not necessarily a desirable trait, given that seed phytate P is not digestible by humans or monogastric animals, and that P exported from cropland is usually lost to the environment (Veneklaas et al. 2012). Adequate P is necessary for seedling vigour if the crop is replanted as seed (Bolland and Baker 1988), and it may be that the selection environment of BJ08-IG in a low-P soil induced greater P allocation to the grain to promote future seedling vigour. This adaptation, while possibly beneficial for seedling vigour in the short term, would hasten P-depletion from soils. Further investigation is needed to determine whether genotypes selected in low-P conditions allocate a greater proportion of P to the grain compared to conventionally-bred varieties.

In addition to overall differences between BJ08-IG and AAC Brandon at anthesis and maturity, the significant genotype by amendment interaction at stem elongation suggests that they may respond differently to the nutrient sources in the early season. Though no differences were detected between the genotypes within the same amendment, there was a trend for BJ08-IG to have numerically higher yields in all treatments except for conventional MAP. This suggests that in the early season, AAC Brandon may be better adapted to access MAP-P, while BJ08-IG is better adapted to access P from organic-matter-based amendments or unfertilized soil. While the interaction was observed only in early-season biomass production and not for P uptake or grain yield, in the relatively cold soils of the Northern Great Plains, early-season P uptake is particularly important to optimize yields (Grant et al. 2001). There is some evidence for wheat genotypes selected under different management having different yield responses to compost in an organically-managed system (Schmidt et al. 2018), supporting the idea that genotypes can be selected to access alternative nutrient sources more efficiently. Further investigation may determine whether changes to root architecture or type and amount of rhizodeposition are driving differences in nutrient acquisition.

Forage crop is better able to access less soluble P sources compared to wheat

The superior performance of struvite in the forage may be caused by the subsurface banding compared to the surface incorporation in wheat, the longer timeframe of the forage experiment (two seasons versus one season), physiological differences between wheat and forage plants in accessing struvite-P, and/or the forage not needing P in as tight a window as wheat due to its perennial nature. Though the difference was less than with struvite, digestate also showed better performance in the forage rather than wheat. Much of the P in the solid-fraction digestate used in this experiment is likely in less soluble forms, perhaps similar to the struvite; in fact, struvite is one of the chemical forms that may be precipitated during the production of digestate (Möller and Müller 2012). This suggests that the forage had some mechanism for accessing less soluble forms of P from digestate and struvite, as well as accessing more soluble forms of P from MAP and frass, which wheat did not have. Frass stood out in both wheat and forage for particularly high P uptake and yield improvements, which were greater than or similar to those of conventional MAP in both crops at all sampling times.

Conclusions

Despite differences in performance between the two cropping systems, all three recycled nutrient sources demonstrated potential to supply P and improve yields in P-depleted, organically-managed production systems. The fact that wheat and forage were not similarly suited to access all of the nutrient sources suggests that greater attention must be paid to crop species and rotation when designing a nutrient plan involving recycled fertilizers containing less soluble P compared to a nutrient plan based on fertilizers containing highly accessible nutrients. Future work in this area should consider the effects of crop rotation on plant access to recycled nutrients. A key component of sustainable systems is that the waste product of one process is a valuable input to another. This research helps to establish recycled nutrient sources as valuable inputs to dryland organically-managed wheat and perennial forage cropping systems. Recycled nutrients improve both organic crop productivity and food system sustainability by improving P cycling from urban areas to agricultural production fields.

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Code availability Not applicable.

Declarations

Conflict of interest The authors declare no conflict of interest.

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