Recycled nutrients as a phosphorus source for Canadian organic agriculture: a perspective

Authors: Nicksy, Jessica, and Entz, Martin H.

Source: Canadian Journal of Soil Science, 101(4) : 571-580

Published By: Canadian Science Publishing

URL: https://doi.org/10.1139/cjss-2021-0014

Canadian Science Publishing

REVIEW

Recycled nutrients as a phosphorus source for Canadian organic agriculture: a perspective

Jessica Nicksy and Martin H. Entz

Abstract: The challenges associated with the global phosphorus (P) cycle are complex and multifaceted, from geological resource limitation, to P deficiency on arable farmland, to environmental contamination via excess P fertilization. Although no single solution can address all of the challenges associated with the P cycle, the principle of circularity provides a framework toward a more sustainable and food-secure P system. Phosphorus deficiency on farmland is widespread, particularly on organically managed farms due to negative P balances in low-input cropping systems. Recycled nutrient sources divert food and human wastes back onto farmland; they have the potential to ameliorate both the global-scale issues of phosphate rock depletion and environmental contamination and the farm-scale issue of P deficiency, particularly for organic farms. For recycled nutrients to act as viable alternatives to conventional nutrient sources, their ability to supply P and improve yields must be demonstrated. This paper provides an introduction to the importance of recycled fertilizer sources in the global P cycle, and the key role they can play on organic farmland in Canada.

Key words: phosphorus, organic management, recycled nutrients, urban waste, circular economy.

Résumé : Le cycle global du phosphore (P) vient avec des difficultés complexes aux multiples facettes, qu'il s'agisse d'une quantité insuffisante pour des raisons géologiques, d'une carence dans les terres arables ou de la pollution de l'environnement attribuable à une fertilisation à outrance. Bien qu'aucune solution ne puisse surmonter toutes ces difficultés à elle seule, le principe de la circularité pave la voie à un système plus durable pour cet élément, se prêtant mieux à la sécurité alimentaire. La carence en phosphore est fréquente dans les terres agricoles, surtout celles consacrées à la culture biologique, car les systèmes de culture incluant une réduction des intrants se caractérisent par un bilan négatif pour le P. Le recyclage des oligoéléments restitue les résidus d'aliments et les vidanges au sol; il pourrait aussi atténuer les problèmes mondiaux que posent l'amenuisement des réserves de phosphate et la contamination de l'environnement, mais aussi ceux, plus locaux, de carence en phosphore, surtout dans les exploitations qui pratiquent l'agriculture biologique. Toutefois, pour que les oligoéléments recyclés deviennent une solution de rechange viable à l'usage classique des engrais, on devra d'abord prouver qu'ils peuvent fournir le P requis et augmenter le rendement. Cet article se veut une introduction à l'importance des engrais recyclés dans le cycle mondial du P et au rôle capital qu'ils peuvent jouer dans l'agriculture biologique au Canada. [Traduit par la Rédaction]

Mots-clés : phosphore, gestion de la matière organique, oligoéléments recyclés, déchets urbains, économie circulaire.

Introduction

Phosphorus (P), an element that is essential to all life as a component of DNA and other biological compounds, faces a "conundrum of deficiency and excess" (Sharpley et al. 2018). Phosphorus deficiency is an important limitation on agricultural yields around the world (Hou et al. 2020); at the same time, excess P flows into waterways are threatening to destabilize the functioning of life-sustaining systems on Earth (Steffen et al. 2015). Further, humans are depleting minable reserves of

Received 17 February 2021. Accepted 16 July 2021.

J. Nicksy. Department of Soil Science, University of Manitoba, Winnipeg, MB R3T 2N2, Canada; Department of Natural Resource Sciences, McGill University, Ste. Anne de Bellevue, QC H9X 3V9, Canada.

M.H. 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).

non-renewable phosphate rock, which is currently used to produce conventional fertilizers (Filippelli 2011; Li et al. 2018).

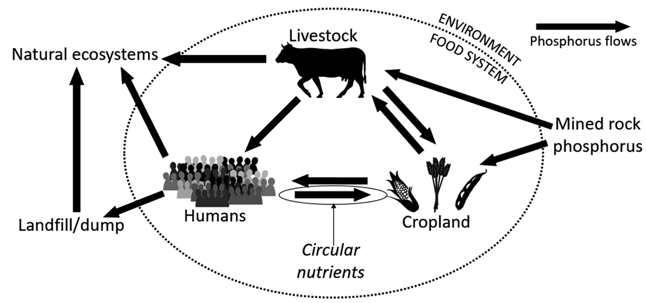
In this paper, we briefly review the challenges posed by P cycling in the global context and the potential of recycling urban nutrients to address some of these challenges. We consider three little-known recycled P sources of urban origin as P fertilizers: frass, the excreta of black soldier fly (BSF; *Hermetia illucens*) larvae used to process urban food waste; anaerobically digested urban food waste; and struvite ($NH_4MgPO_4 \cdot 6H_2O$), a mineral extracted from municipal wastewater streams. We examine the role of P in organic management systems, which are often P deficient. Increased use of recycled P on organic farms could be a "win-win" for both organic farmers and the fledgling recycled nutrients sector. Organic farms would benefit from increased availability of sustainable P sources. Meanwhile, the organic premiums which are available to organic farmers could support the purchase of recycled P fertilizers, which generally remain more expensive than conventional fertilizers. We examine the Canadian context and consider whether P recycling can substantially reduce our reliance on imported P fertilizers. Further, we make a case study of the province of Manitoba, and how P cycle challenges within the province represent microcosms of challenges faced by Canada and the world. We argue that although efficient recycling of urban P in Canada cannot eliminate our reliance on fertilizer P imports, the goal of recycling urban P should be pursued, particularly in the context of organic farming.

Global P Cycle

Phosphorus plays a pivotal role at the intersection of food, water, and energy security; it is a non-renewable resource that is an essential plant nutrient for food and biofuel crops, but a harmful environmental contaminant in waterways (Jarvie et al. 2015). Prior to the mid-late 19th century, farms relied on local nutrient sources (e.g., manure and human excreta) for nutrient replenishment (Cordell et al. 2009). As P is a nutrient with no significant gaseous atmospheric source or sink (Liu et al. 2008), this made for fairly closed local P cycles. Mining, first of guano and then of phosphate rock, as P fertilizer, along with global food trade and reduced recycling of human excreta with the advent of flush toilets, shifted the system from one of local circularity to global linearity (Cordell et al. 2009).

Phosphorus now enters the food system via fertilizer mined from non-renewable and often geographically distant rock phosphate reserves external to the food system. It is exported to population-dense urban centers via crops, and it leaves the food system via food and human waste entering landfills and waterways, along with P runoff from livestock systems and arable land (Fig. 1). Remaining reserves of rock phosphate may be depleted in as little as 70–140 yr based on projected

Fig. 1. Conceptual food system model for phosphorus flows.



demand (Li et al. 2018). Phosphate rock deposits are formed on a geological time scale of millions of years, far slower than human activity is now depleting them (Filippelli 2011). A model of global P flows estimates that only 17% of organic solid food waste P and 10% of human waste P are recycled to arable soil (Cordell et al. 2009). Animal manure fares better, with over 50% of animal manure being returned to arable soil (Cordell et al. 2009); however, animal manure is often abundant in regions with excess soil P, and scarce in regions of soil P deficiency, due to the concentration of animal production located far from feed production (Jarvie et al. 2015).

Concentration of animal production depending on imported feed (and the associated P therein) can lead to excess P accumulation in soils. Manure and other organic amendments are generally applied based on crop nitrogen (N) requirements, which leads to increased soil P because crop offtake N:P ratios are higher than the N:P ratio in most organic amendments (Sharpley and Moyer 2000; Eghball 2002). High soil P level, and resultant increased environmental P loss in the runoff, is a challenge which plagues regions of high livestock density like the Chesapeake Bay watershed on the American East Coast (Beegle 2013). Although runoff P losses are generally not agronomically important [e.g., $<1\ kg \cdot ha^{-1} \cdot yr^{-1}$ (Tiessen et al. 2010)], they are environmentally impactful as they can contribute significantly to P loading in water bodies (Schindler et al. 2012). The same problem exists where humans are concentrated in urban settings and produce substantial P waste (Jarvie et al. 2015), though urban P is more commonly sent to landfills or released to waterbodies directly rather than re-applied to agricultural land (Cordell et al. 2009). Steffen et al. (2015) assessed science-based planetary boundaries for several Earth system processes, and found that humans have already exceeded the "safe zone" for P flows to water bodies; current flows place us at high risk of ocean anoxia and freshwater eutrophication.

Phosphorus and Organic Management

Although excess P plagues some regions, P deficiency is equally a threat to food system sustainability and security. A recent meta-analysis found that 49% of cropland globally is P limited (Hou et al. 2020). Phosphorus limitation is especially prevalent on organic farms, where options for nutrient import are limited. Organic farms typically rely on biological N fixation with leguminous green manures, but this leaves them at risk of negative P balances, resulting in P "mining" and eventual P deficiency (Welsh et al. 2009; Reimer et al. 2020). Surveys of organic farms on the Northern Great Plains found P deficiency on farms with a long history of organic management (Entz et al. 2001; Knight et al. 2010). Similarly, farms managed organically for more than 15 yr in England had lower soil P than conventionally managed farms (Gosling and Shepherd 2005). Phosphorus "mining" on organic farmland contradicts the organic ethic of ecology and undermines the long-term sustainability of organic farming.

Sir Albert Howard, a pioneer of the organic movement, recognized the importance of recycling organic wastes to the soil. His "Law of Return" advocated the use of sewage sludge as a means of returning fertility and organic matter to the soil (Heckman 2006). This idea of designing systems for circularity was prescient, coming long before the recognition that humans were depleting non-renewable P reserves. Given this history, one might expect organic farmers and researchers to be at the forefront of using urban wastes as agricultural amendments; however, concerns about potentially toxic elements and organic compounds, particularly in human wastes, are in tension with the adoption of urban wastes streams in organic agriculture (Möller et al. 2018). Phosphorus in human wastewater accounts for the largest proportion of urban P (representing 50%–60% of mined P fertilizer applied in Europe) and thus cannot be ignored by the organic community when considering sustainable P sources (Möller et al. 2018). The conversation is perhaps furthest advanced in Europe, where a survey of stakeholders in the organic industry including farmers and certifiers found that on average 60% viewed the use of human urine and sewage sludge in organic agriculture positively (Løes 2016), and struvite precipitated from municipal wastewater is in the process of gaining legislative approval for use in organic agriculture in the European Union (Cuoco and Hermann 2020). Meanwhile, struvite from municipal wastewater was reviewed but not approved by the Canadian Technical Committee on Organic Agriculture; however, struvite from plant or animal sources was approved (Organic Federation of Canada 2020).

If organic agriculture regulation can be shifted to support the use of recycled nutrients, organic farmers are uniquely positioned to adopt them. Sources of recycled P are often more expensive than conventional sources, and organic premiums in combination with restriction on conventional fertilizer use may make recycled nutrient sources economically feasible for organic farmers, whereas they would not be feasible for conventional farmers.

If recycled nutrients are to be feasible components of the P cycle, they must be effective sources of P for crop plants. Some current treatments used to chemically remove P from wastewater streams prior to discharge may render that P unavailable in sewage sludge (Möller et al. 2018). For example, aluminium (Al) and iron (Fe) treatments cause the precipitation of low-solubility Fe and Al phosphates, as well as strong adsorption of P to Fe and Al hydroxides, resulting in P availability from the sewage sludge being less than 25% compared with triple super phosphate (Torri et al. 2017).

Although biosolids and composted household food waste are probably the most familiar sources of recycled nutrients, many other processing options for food and human waste are available. These techniques may be less well known but can provide additional co-benefits within and beyond the food system. For example, anaerobic digestion of food waste produces methane biogas which can be used in place of fossil fuels (Wainaina et al. 2020). Insects which are used to process food waste produce not only a recycled nutrient source in their frass (excreta), but their biomass itself is also a useful high-protein food or feed source (Čičková et al. 2015). When struvite is precipitated from municipal wastewater systems, it not only produces a high-P fertilizer but also removes P before it can enter waterways and contribute to eutrophication (Kumar and Pal 2015). Further, struvite has sufficiently high P content that it may be feasible to transport it to regions of P deficit.

We consider and review these three recycled nutrient sources, which are commercially available in Canada, though not widely used by farmers. The digestate and frass we consider are sourced from processing techniques for urban food waste, whereas struvite is sourced from municipal wastewater. Wyngaarden et al. (2020) point out that an efficient agri-food system would divert food waste to be productively used as livestock feed, though they acknowledge the complexities of utilizing some waste streams, particularly household food waste, in this way. We suggest that an efficient agri-food system would divert as much food waste as feasible to feed livestock and use other methods such as digestion, insect processing, or composting, to convert the remainder into agronomically useful forms.

Food-waste-derived frass and digestate are approved for use in organic production systems. Municipally derived struvite remains, for the moment, prohibited in organic agriculture in Canada, though it will likely be reviewed again in 2025 (Organic Federation of Canada 2020). In the meantime, livestock- or plant-derived struvite has been approved for use in organic agriculture, and thus the inclusion of municipally derived struvite is relevant for organic farmers in the short as well as long term (Canadian General Standards Board 2018).

Table 1. Results of a 5 November 2020 literature search in all Web of Science databases.

	Amendment search term[a]	No. of results
Conventional sources	Ammonium phosphate	11 760
	Manure	72 952
Circular sources	Struvite	1005
	Frass	61
	Anaerobic digestate	171

[a]The full search term was the amendment search term + fertilizer OR amendment. Note that these values are illustrative of the order of magnitude differences in the bodies of literature only and do not represent the number of studies assessing agronomic or fertilizer potential of each product; many of the search results focus on the creation of the amendments and only mention fertilizer or amendment potential in passing, but were still found in this search.

These recycled nutrient sources are understudied compared with conventional sources such as manure and mono-ammonium phosphate (MAP). Results of a rudimentary Web of Science search reveal that publications on conventional P sources are orders of magnitude more numerous than publications on the recycled nutrient sources evaluated in this study (Table 1). A greater body of literature is required to establish whether these nutrient sources can effectively supply P in organic systems.

Frass

In Canada, a frass (insect excreta) product is currently derived from BSF larvae fed a diet of pre-consumer (restaurant and grocery) non-meat waste. Insects are gaining attention in the sustainable food sphere due to their lower environmental impacts and their feed-to-protein conversion ratio compared with conventional livestock (Fan et al. 2015; Wegier et al. 2018). Using insects as livestock feed reduces the cropland required to grow feed, and thus frees this land for the production of human consumables (Wegier et al. 2018). In addition, insects can be eaten directly as sustainable protein sources for humans, though cultural norms often inhibit this use (Fan et al. 2015). BSF larvae have good potential as processors of urban food waste due to their ability to eat a wide variety of organic materials (Čičková et al. 2015).

Few peer-reviewed publications exist on the fertilizer potential of BSF larvae frass, with the majority of the literature focussing on the production of insect biomass (e.g., Pastor et al. 2015; Kierończyk et al. 2020). The only studies known to us that specifically assess frass' P fertilization properties were conducted by the authors (Nicksy 2021; Nicksy et al. 2021). Field studies in wheat and alfalfa, and a pot study with Italian ryegrass, showed increased P uptake from the frass treatment compared with the non-fertilized control, and similar P uptake from frass compared with soluble MAP in all crops (Nicksy 2021; Nicksy et al. 2021). A different study mixed various proportions of frass (from insects grown with an artificial diet rather than food waste) with peat as a growing medium for basil (*Ocimum basilicum* L.), tomato (*Solanum lycopersicum* L.), and lettuce (*Lactuca sativa* L.) (Setti et al. 2019). Rates up to 20% frass by volume improved plant growth, but a high proportion of frass suppressed plant growth. Another pot study using a 2:1 ratio of soil to frass from food-waste-fed BSF larvae found growth suppression of maize (*Zea mays* L.) in the frass treatment (Alattar et al. 2016). These studies indicate that high proportions of frass relative to soil may be phytotoxic, perhaps due to salinity or high ammonium concentration of the frass. Kebli and Sinaj (2017) found positive results of food-waste-fed BSF frass applied based on an N rate in a pot study using lettuce and ryegrass. In ryegrass, frass produced similar yields compared with amineral fertilizer in two of three soils. In lettuce, frass had similar or greater yield compared with the mineral fertilizer in the low-pH sandy soil but lower yield in the two neutral to high-pH soils. Frass consistently improved yields compared with the control for both lettuce and ryegrass. Choi et al. (2009) found similar growth rate of Chinese cabbage (*Brassica rapa* L.) with a BSF frass and a commercial fertilizer, though the identity of the commercial fertilizer is not specified. Gärttling et al. (2020) found lower N supply from BSF frass compared with a mineral fertilizer in a maize pot study. These studies vary in whether the BSF larvae are fed urban food waste or another feed substrate, and the type of feed used may be important in determining frass fertilizer properties. Klammsteiner et al. (2020) found significantly different pH, electrical conductivity, and N content of BSF frass from larvae fed three different diets (P content not reported), although the three frass types resulted in similar growth of ryegrass to each other and a mineral fertilizer when applied based on an N rate. Frass efficacy may be dependent on BSF feedstock as well as pH or other soil properties, and further research is needed to delineate these relationships, particularly with respect to its P properties.

Anaerobic digestate

Digestate can be produced from a number of organic waste materials including livestock manure, sewage sludge, food processing waste, and retail waste. In this paper, we focus on digestate of food waste. Anaerobic digestion is the degradation of organic matter by natural microbial communities in the absence of oxygen, which produces a gaseous "biogas" mix predominantly composed of CH_4 and CO_2 (Wainaina et al. 2020). The raw biogas can be used directly in electricity and heat generation, or upgraded to be used as a vehicle fuel or injected into natural gas lines (Wainaina et al. 2020). Anaerobic digestion is a promising technology for processing food waste within the food-energy-water nexus because it produces clean energy and contributes to the circular use of nutrients (Kibler et al. 2018; Wainaina et al. 2020). In addition, anaerobic digestion has the potential to produce other valuable products like hydrogen gas and volatile fatty acids, though these processes are currently in the research stage (Ma and Liu 2019; Wainaina et al. 2020).

Liquid and solid fractions of wet digestate can be applied together or separately to agricultural land as nutrient and organic matter sources, with the solids often undergoing an aerobic composting phase prior to land application (Möller and Müller 2012; Kibler et al. 2018; Chojnacka et al. 2019). Solid fractions of anaerobic digestate tend to have higher P concentrations than liquid (Nkoa 2014). The solid fraction of digestate may be dried and pelletized for ease of application with farm machinery and to increase the economic transport distance of the product. Digestion often causes an increase in pH and formation of minerals like Ca or Mg phosphates and struvite within the digestate, though this may not necessarily hamper its efficacy as a P source (Möller and Müller 2012). For example, Haraldsen et al. (2011) found statistically similar P uptake and grain yield for a liquid food waste digestate and a synthetic fertilizer. The efficacy of P supply from food waste digestate may depend on the fraction (solid or liquid) and the pH of the soil. In a study of potential recycled P fertilizers, Brod et al. (2015) found a greater fraction of recalcitrant species, and especially acid-soluble Ca and Mg phosphates in solid compared with liquid food waste digestate. A bioassay using ryegrass in the same study found lower P uptake from the solid fraction compared with the liquid fraction and a synthetic fertilizer at soils of pH 5.5 and 6.9. In the higher pH soil, there was a significant relationship between P uptake and the fraction of acid-soluble recalcitrant in the amendments, indicating that the presence of these low-solubility precipitates is a greater hindrance to P uptake at higher pH (Brod et al. 2015). Nicksy (2021) found that digestate increased P uptake compared with the non-fertilized control in all of alfalfa, wheat, and Italian ryegrass, but that it had lower P uptake compared with soluble MAP in wheat and ryegrass.

Post-digestion processes may also impact P availability of anaerobic digestates. Ross et al. (2018) found that addition of a pelletized composted digestate did not increase double lactate extractable soil test P compared with a control, whereas the unpelletized digestate did increase available P in an oat (*Avena sativa* L.) pot experiment. Further study of the impact of processes like drying and pelletization on P availability in digestate products is warranted. In Canada, food waste digestate is beginning to be used on organic farms as a nutrient source.

Struvite

Struvite is an ammonium magnesium phosphate mineral ($NH_4MgPO_4{\cdot}6H_2O$) which precipitates naturally in sewage treatment facilities and can be an operational problem when it clogs pipes (Kumar and Pal 2015); however, it is possible to intentionally precipitate struvite in wastewater treatment facilities through manipulation of pH to around 9.0 and sometimes addition of Mg (Kumar and Pal 2015). Commercially available struvite has a high P content (NPK 5–28–0–10 Mg) on the same order of magnitude as mined synthetic P fertilizers like MAP (11–52–0). This makes struvite a feasible option for shipping P from high-P to P-depleted regions (Metson et al. 2016). However, Möller et al. (2018) pointed out that struvite does not contribute organic matter and micronutrients to the soil; this may make it a less desirable overall soil amendment compared with organic-matter-based amendments like sewage sludge or food waste compost, at least in areas where those organic-matter-based amendments are readily available. From a circular food system perspective, struvite's most important role is in moving P from areas where it is in excess to where it is needed; it may not be the most appropriate amendment in regions where there are abundant organic-matter-based P sources available.

Struvite has been widely found to have similar P availability compared with conventional fertilizers (e.g., Cabeza et al. 2011; Katanda et al. 2016); however, many struvite studies are conducted in pots with ground struvite instead of granules, as would be applied in the field. There appears to be an interactive effect between granule size and soil pH on struvite dissolution. Degryse et al. (2017) found that ground struvite dissolved well at a range of pH from 5.9 to 8.5, but granular struvite dissolved much more slowly in high-pH soils compared with low-pH soils. Another complicating factor is crop species. Buckwheat (*Fagopyrum esculentum* Moench) has been shown to be more efficient at accessing struvite than wheat, perhaps due to buckwheat's ability to exude organic acids and induce struvite dissolution (Talboys et al. 2016). Nicksy (2021) found that struvite increased P uptake compared with a non-fertilized control in alfalfa and ryegrass but not in wheat. In alfalfa, P uptake from struvite was similar to that of soluble MAP. Two meta-analyses of struvite found the good performance of struvite compared with synthetic fertilizers, but one found

Table 2. Comparison of annual human-generated phosphorus (P) (from both food and human waste) in Canadian provinces with organic cropland and all cropland.

	Human P generated ($kg \cdot yr^{-1}$)	Organic cropland (ha)	All cropland (ha)	Human P per organic cropland ($kg \cdot ha^{-1}$)	Human P per all cropland ($kg \cdot ha^{-1}$)
British Columbia	4 090 288	11 020	580 820	371	7.04
Alberta	3 579 114	120 475	10 223 079	30	0.35
Saskatchewan	966 550	250 662	16 385 436	4	0.06
Manitoba	1 124 961	21 084	4 666 063	53	0.24
Ontario	11 834 675	36 843	3 650 789	321	3.24
Quebec	7 184 638	57 467	1 866 829	125	3.85
Atlantic	2 053 323	3288	417 593	624	4.92
Territories	99 972	69	2557	1453	39.10
Total	**30 933 521**	**500 909**	**37 793 166**	**62**	**0.82**

decreasing efficacy of struvite with increasing pH (Hertzberger et al. 2020), whereas the other did not (Möller et al. 2018). In the more recent and comprehensive meta-analysis by Hertzberger et al. (2020), only 8% of reviewed experiments were field studies, pointing to the need for more field research in struvite, especially across a range of soil pH values. It has been postulated that struvite could have greater P recovery efficiency than highly soluble fertilizers, as its slow-release nature reduces its susceptibility to adsorption and precipitation reactions which limit P recovery from high solubility fertilizers; however, current evidence does not suggest that struvite P is recovered more efficiently than high solubility fertilizers, except perhaps in low-pH soils (Hertzberger et al. 2020). Struvite is currently being extracted from wastewater in several large Canadian cities.

The Canadian Context

Phosphate rock reserves are unevenly distributed globally, with six countries controlling 90% of high-grade reserves and Morocco alone controlling 74% (Cordell and White 2014). Geopolitical risks concerning price setting and political instability influencing global P trade arise from this uneven distribution (Cordell and White 2014). Canada produces no P fertilizer of its own, instead relying on P fertilizer imports (Statistics Canada 2021*a*), making it particularly susceptible to possible instability of P supply. Recycled P sources are one means to mitigate this risk; however, Canada exports more P (200 Gg $P \cdot yr^{-1}$) than it imports (30 Gg $P \cdot yr^{-1}$) as agricultural products, leading to a P deficit of 170 Gg $P \cdot yr^{-1}$, or the equivalent of about 4.5 $kg \cdot ha^{-1}$ of Canadian cropland (Nesme et al. 2018). This suggests that even perfect P recycling could not sufficiently replace P lost via agricultural exports.

We used estimates of P generated in food and human waste per capita from Metson et al. (2016), along with population and fertilizer information from Statistics Canada (Statistics Canada 2017, 2021*b*) to estimate the amount of P generated by Canadians as food and human waste each year and compared it with fertilizer P imports. Based on estimates that an individual generates 0.39 kg P in food waste and 0.49 kg P in human waste per year (Metson et al. 2016), and Canada's 2016 population of approximately 35.2 million (Statistics Canada 2017), Canadians generate about 31 Gg of P in waste annually (Table 2). This is equivalent to 8% of Canada's annual P fertilizer imports of 390 Gg P (Statistics Canada 2021*b*), in contrast to Europe where human wastewater alone accounts for 50%–60% of fertilizer P imports (Möller et al. 2018). Human sources of P alone cannot substantially replace mined P fertilizer imports in Canada, but they are an important step towards sustainability. It should be noted that Canadian imports of fertilizer P (390 Gg) far exceed Canada's annual agricultural products deficit of around 170 Gg, as reported by Nesme et al. (2018), and that more efficient distribution and use of P could reduce the amount of fertilizer P which is needed. In addition, recycled P sources may play a critical role in returning P to organic cropland in particular.

We use organic cropland data from the Canada Organic Trade Association (2018) and total cropland data from Statistics Canada (2016) to evaluate how much P per hectare urban sources could supply by province (Table 2). Based on organic cropland of 500 909 ha in 2018, human P produced annually in Canada is equivalent to 62 kg $P \cdot ha^{-1}$ of certified organic land. This far exceeds the range of P removal values for typical crops in Manitoba (from 7.5 kg $P \cdot ha^{-1}$ in flax to 33 kg $P \cdot ha^{-1}$ in alfalfa) (Manitoba Agriculture 2007), indicating that the human P resource could be more than sufficient to meet P needs of Canadian organic farms, if it were efficiently redistributed onto organically managed land. This is important when considered in the context that many organic farmers experience P depletion and deficiency on their farms, and struggle to find adequate manure resources to maintain a neutral P balance. Human-generated P is in clear excess of crop requirements for organic cropland in most provinces (Table 2). Provinces with a higher ratio of population to cropland (e.g., Ontario, Quebec, and

BC) have very high rates of human P per hectare of organic farmland. Meanwhile, Saskatchewan, which has the most organic cropland alongside a small human population, generates only 5 kg P·ha^{-1} for organic cropland. This suggests the need for redistribution of recycled P within Canada, from areas of higher population density to lower density. When all cropland (not just organic) is considered, it is clear that human-generated recycled P is insufficient to replace P removed via crops (Table 2). Livestock P recycling provides another avenue to replace harvested P. However, given the Canadian annual deficit of 4.5 kg P·ha^{-1} in agricultural products, recycled P would need to be imported from other countries to fully eliminate the need for mined fertilizer P.

Phosphorus fertilizers with an urban food waste feed stock are generally permitted in organic agriculture; however, organic regulation currently prohibits the use of human-waste sourced nutrients (Canadian General Standards Board 2018). This is a substantial barrier to maximizing the potential of recycled nutrients in organic agriculture. In particular, the prohibition of municipally derived struvite, which as a mineral fertilizer has a P content in the same order of magnitude as conventional P fertilizers and can, therefore, be shipped long distances economically, prevents the redistribution of P from P-rich regions to P-poor regions.

Case study: P in Manitoba

Many of the P challenges described at the global level exist within Manitoba: an overall P deficit, especially on organic farms; P surpluses in some areas due to livestock concentration; and rapid eutrophication of the largest lake in Manitoba due to P loading.

Although no comprehensive P flow assessment has been performed for Manitoba, Loro et al. (2013) estimated P budgets for agricultural soils in rural municipalities of Manitoba based on 2011 livestock numbers. Overall, Manitoba's agricultural land lost P at a rate of over 13 Gg P·yr^{-1} in 2011, or 2.0 kg P ha^{-1}·yr^{-1}. This includes the import of synthetic fertilizer, which accounts for 71% of P inputs; if synthetic fertilizer were not included the P deficit would be 8.7 kg P·ha^{-1}. Thus, Manitoba is currently heavily dependent on nonrenewable P fertilizer imports for crop productivity. Insufficient manure resources pose an extra risk to Manitoba's organic farms, which cannot rely on synthetic fertilizer imports to balance their P budgets.

Manitoba's P deficit problem is exacerbated by inefficient use of manure P. Nine of 78 rural municipalities in Manitoba actually have P surpluses due to concentration of livestock in these areas (Loro et al. 2013). Seven of the nine could reach P balance by removing synthetic P imports and instead relying exclusively on manure P. The other two (Hanover and La Broquerie) have insufficient cropland relative to livestock to reach P balance even if they halted the use of synthetic fertilizer. Livestock densities have been well correlated to P concentration in runoff in Manitoba, highlighting the environmental risk of livestock concentration (Salvano et al. 2009). These municipalities highlight that even regions with an overall P deficit, like Manitoba, can have localized areas of surplus P and increased P runoff risk when livestock are concentrated rather than distributed across the landscape.

Notably, human sources of P were not considered in the Loro et al. (2013) report. Based on Manitoba's 2019 population of 1 372 708 (Government of Manitoba 2019), and P in human and food waste of 0.49 and 0.39 kg P·person^{-1}·yr^{-1}, respectively (Metson et al. 2016), human P sources could theoretically contribute 1.2 Gg P·yr^{-1} to Manitoba's P cycle. This value is small compared with manure P produced in 2011 (17.1 Gg P) (Loro et al. 2013), but it could slightly offset the P import requirements of the province. In addition, if the focus is narrowed to the use of recycled nutrients in organic agriculture, human P produced in Manitoba could supply 79 kg P·ha^{-1} of organic cropland.

Further, diverting Manitoba's human P pool to agricultural land with a P deficit has positive environmental implications. Phosphorus in Manitoba wastewater is an important contributor to P loading in Lake Winnipeg, accounting for 9% of the total P load to Lake Winnipeg and 20% of Manitoba P sources (Lake Winnipeg Stewardship Board 2006). Lake Winnipeg is the world's 10th largest freshwater lake, is shallow, and has the highest ratio of watershed area to lake surface area of any great lake worldwide, rendering it particularly susceptible to eutrophication (Lake Winnipeg Stewardship Board 2006). Lake Winnipeg has undergone rapid eutrophication since the mid-1990s, driven by P loading from increases in livestock and human populations (Schindler et al. 2012).

Utilization of recycled nutrient sources in Manitoba can slightly decrease the province's P deficit and provide P import options for organic farmers while reducing the human contribution to P loading and eutrophication in Lake Winnipeg and other water bodies. To meaningfully reduce its reliance on mined P fertilizer, Manitoba would also need to procure recycled P from regions of P excess in other parts of the country or around the world.

Conclusion

Incorporating recycled nutrients into agricultural systems is vital for long-term food system security and sustainability, both in Canada and across the globe. We have briefly reviewed three commercially available recycled P fertilizers. Frass, digestate, and struvite all show similar to somewhat reduced P supplying properties compared with conventional fertilizers, though the data on P supply from frass is limited to the author's M.Sc. thesis (Nicksy 2021). Barriers to increased farmer adoption of these recycled P sources are likely to be based on fertilizer availability, logistics of transport, and economic considerations, rather than concerns about P availability from these products.

We have further considered the amount and potential role of recycled P from human sources in Canada. Waste P generated by the Canadian population exceeds the P needs of organic farmland in Canada, and it could contribute to the amelioration of P deficiency on these lands; however, inputs from human P are insufficient to substantially decrease P fertilizer imports. Therefore, we suggest that the organic sector is uniquely poised to play a key role in promoting and adopting recycled P sources in organic agriculture. Organic farmers have access to organic premiums that may make more expensive recycled P sources economically feasible. They are also among the most at risk of P depletion and deficiency on their farms due to negative farm-gate P balances, restrictions on the use of conventional fertilizers, and lack of sufficient local manure resources. Recycled nutrient use must not be limited to organic farmers, as human P is in excess of organic crop needs, but the organic sector can play an important role in expanding the use of these nutrient sources. Changes in organic regulation to allow the use of human-derived nutrients are required to fulfill this potential.

Recycled nutrient sources will play a vital role in preserving the long-term sustainability of global food systems. Canadian farmers, and especially organic farmers, have the potential to help drive adoption of recycled nutrients and benefit from their use in ameliorating P deficiency.

References

Alattar, M., Alattar, F., and Popa, R. 2016. Effects of microaerobic fermentation and black soldier fly larvae food scrap processing residues on the growth of corn plants (*Zea mays*). Plant Sci. Today, **3**: 57–62. doi:10.14719/pst.2016.3.1.179.

Beegle, D. 2013. Nutrient management and the Chesapeake Bay. J. Contemp. Water Res. Educ. **151**: 3–8. doi:10.1111/j.1936-704X.2013.03146.x.

Brod, E., Øgaard, A.F., Hansen, E., Wragg, D., Haraldsen, T.K., and Krogstad, T. 2015. Waste products as alternative phosphorus fertilisers part I: inorganic P species affect fertilisation effects depending on soil pH. Nutr. Cycl. Agroecosyst. **103**: 167–185. doi:10.1007/s10705-015-9734-1.

Cabeza, R., Steingrobe, B., Römer, W., and Claassen, N. 2011. Effectiveness of recycled P products as P fertilizers, as evaluated in pot experiments. Nutr. Cycl. Agroecosyst. **91**: 173–184. doi:10.1007/s10705-011-9454-0.

Canada Organic Trade Association. 2018. Organics in Canada. [Online]. Available from: https://canada-organic.myshopify.com/collections/organic-agriculture-by-the-numbers/products/organic-agriculture-by-the-numbers-2018-data.

Canadian General Standards Board. 2018. Organic production systems permitted substances lists. Gatineau. [Online]. Available from: www.publications.gc.ca/site/eng/9.854645/publication.html.

Choi, Y., Choi, J., Kim, J., Kim, M., Kim, W., Park, K., and Bae, S. 2009. Potential usage of food waste as a natural fertilizer after digestion by *Hermetia illucens* (Diptera: Stratiomyidae). Int. J. Ind. Entomol. **19**: 171–174.

Chojnacka, K., Gorazda, K., Witek-Krowiak, A., and Moustakas, K. 2019. Recovery of fertilizer nutrients from materials — contradictions, mistakes and future trends. Renew. Sustain. Energy Rev. **110**: 485–498. doi:10.1016/j.rser.2019.04.063.

Čičková, H., Newton, G.L., Lacy, R.C., and Kozánek, M. 2015. The use of fly larvae for organic waste treatment. Waste Manag. **35**: 68–80. doi:10.1016/j.wasman.2014.09.026. PMID:25453313.

Cordell, D., Drangert, J.O., and White, S. 2009. The story of phosphorus: Global food security and food for thought. Glob. Environ. Chang. **19**: 292–305. doi:10.1016/j.gloenvcha.2008.10.009.

Cordell, D., and White, S. 2014. Life's bottleneck: sustaining the world's phosphorus for a food secure future. Annu. Rev. Environ. Resour. **39**: 161–188. doi:10.1146/annurev-environ-010213-113300.

Cuoco, E., and Hermann, L. 2020. Object: inclusion of recovered struvite and calcined phosphate in Organic Farming Regulation annexes. IFOAM EU, Belgium. [Online]. Available from: https://phosphorusplatform.eu/images/download/Joint-letter-ESPP-IFOAM-EU-recovered-phosphates-17_6_20.pdf [2 Dec. 2020].

Degryse, F., Baird, R., da Silva, R.C., and McLaughlin, M.J. 2017. Dissolution rate and agronomic effectiveness of struvite fertilizers — effect of soil pH, granulation and base excess. Plant Soil, **410**: 139–152. doi:10.1007/s11104-016-2990-2.

Eghball, B. 2002. Soil properties as influenced by phosphorus- and nitrogen-based manure and compost applications. Agron. J. **94**: 128–135. doi:10.2134/agronj2002.0128.

Entz, M.H., Guilford, R., and Gulden, R. 2001. Crop yield and soil nutrient status on 14 organic farms in the eastern portion of the northern Great Plains. Can. J. Plant Sci. **81**: 351–354. doi:10.4141/P00-089.

Fan, J.W., Du, Y.L., Turner, N.C., Wang, B.R., Fang, Y., Xi, Y., et al. 2015. Changes in root morphology and physiology to limited phosphorus and moisture in a locally-selected cultivar and an introduced cultivar of *Medicago sativa* L. growing in alkaline soil. Plant Soil, **392**: 215–226. doi:10.1007/s11104-015-2454-0.

Filippelli, G.M. 2011. Phosphate rock formation and marine phosphorus geochemistry: the deep time perspective. Chemosphere, **84**: 759–766. doi:10.1016/j.chemosphere.2011.02.019. PMID:21376366.

Gärttling, D., Kirchner, S.M., and Schulz, H. 2020. Assessment of the N- and P-fertilization effect of black soldier fly (Siptera: Stratiomyidae) by-products on maize. J. Insect Sci. **20**: 1–11. doi:10.1093/jisesa/ieaa089.

Gosling, P., and Shepherd, M. 2005. Long-term changes in soil fertility in organic arable farming systems in England, with particular reference to phosphorus and potassium. Agric. Ecosyst. Environ. **105**: 425–432. doi:10.1016/j.agee.2004.03.007.

Government of Manitoba. 2019. Manitoba Population Report. Winnipeg. [Online]. Available from: www.gov.mb.ca/health/population/pr2019.pdf [4 Dec. 2020].

Haraldsen, T.K., Andersen, U., Krogstad, T., and Sørheim, R. 2011. Liquid digestate from anaerobic treatment of source-separated household waste as fertilizer to barley. Waste Manag. Res. **29**: 1271–1276. doi:10.1177/0734242X11411975. PMID:21746761.

Heckman, J. 2006. A history of organic farming: transitions from Sir Albert Howard's War in the Soil to USDA National Organic Program. Renew. Agric. Food Syst. **21**: 143–150. doi:10.1079/RAF2005126.

Hertzberger, A.J., Cusick, R.D., and Margenot, A.J. 2020. A review and meta-analysis of the agricultural potential of struvite as a phosphorus fertilizer. Soil Sci. Soc. Am. J. **84**: 653–671. doi:10.1002/saj2.20065.

Hou, E., Luo, Y., Kuang, Y., Chen, C., Lu, X., Jiang, L., et al. 2020. Global meta-analysis shows pervasive phosphorus limitation of aboveground plant production in natural terrestrial ecosystems. Nat. Commun. **11**: 637. doi:10.1038/s41467-020-14492-w. PMID:32005808.

Jarvie, H.P., Sharpley, A.N., Flaten, D., Kleinman, P.J.A., Jenkins, A., and Simmons, T. 2015. The pivotal role of phosphorus in a resilient water–energy–food security nexus. J. Environ. Qual. **44**: 1049–1062. doi:10.2134/jeq2015.01.0030. PMID:26437086.

Katanda, Y., Zvomuya, F., Flaten, D., and 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. doi:10.2136/sssaj2015.07.0280.

Kebli, H., and Sinaj, S. 2017. Agronomic potential of a natural fertiliser based on fly larvae frass. Agrar. Schweiz, **8**: 88–95.

Kibler, K.M., Reinhart, D., Hawkins, C., Motlagh, A.M., and Wright, J. 2018. Food waste and the food-energy-water nexus: a review of food waste management alternatives. Waste Manag. **74**: 52–62. doi:10.1016/j.wasman.2018.01.014. PMID:29366796.

Kierończyk, B., Sypniewski, J., Rawski, M., Czekała, W., Swiatkiewicz, S., and Józefiak, D. 2020. From waste to sustainable feed material: the effect of *Hermetia illucens* oil on the growth performance, nutrient digestibility, and gastrointestinal tract morphometry of broiler chickens. Ann. Anim. Sci. **20**: 157–177. doi:10.2478/aoas-2019-0066.

Klammsteiner, T., Turan, V., Fernández-Delgado Juárez, M., Oberegger, S., and Insam, H. 2020. Suitability of black soldier fly frass as soil amendment and implication for organic waste hygienization. Agronomy, **10**: 1578. doi:10.3390/agronomy10101578.

Knight, J.D., Buhler, R., Leeson, J.Y., and Shirtliffe, S.J. 2010. Classification and fertility status of organically managed fields across Saskatchewan, Canada. Can. J. Soil Sci. **90**: 667–678. doi:10.4141/cjss09082.

Kumar, R., and Pal, P. 2015. Assessing the feasibility of N and P recovery by struvite precipitation from nutrient-rich wastewater: a review. Environ. Sci. Pollut. Res. **22**: 17453–17464. doi:10.1007/s11356-015-5450-2.

Lake Winnipeg Stewardship Board. 2006. Reducing nutrient loading to Lake Winnipeg and its watershed: our collective responsibility and commitment to action. [Online]. Available from: digitalcollection.gov.mb.ca/awweb/pdfopener?smd=1&did=16507&md=1.

Li, B., Boiarkina, I., Young, B., Yu, W., and Singhal, N. 2018. Prediction of future phosphate rock: a demand based model. J. Environ. Inform. **31**: 41–53.

Liu, Y., Villalba, G., Ayres, R.U., and Schroder, H. 2008. Global phosphorus flows and environmental impacts from a consumption perspective. J. Ind. Ecol. **12**: 229–247. doi:10.1111/j.1530-9290.2008.00025.x.

Løes, A. 2016. What does the organic sector think about different phosphorus fertilizers? Norsøk Report.

Loro, P., Arzandeh, M., Brewin, D., Akinremi, W., Gyles, C., and Ige, D. 2013. Estimating soil phosphorus budgets for rural municipalities in Manitoba. [Online]. Available from: www.manitobapork.com/images/MLMMI/2010-19L/Final Report 2010-19-L Estimating Soil Phosphorus Budgets by Municipality.pdf [4 Dec. 2020].

Ma, Y., and Liu, Y. 2019. Turning food waste to energy and resources towards a great environmental and economic sustainability: An innovative integrated biological approach. Biotechnol. Adv. **37**: 1–11. doi:10.1016/j.biotechadv.2019.06.013.

Manitoba Agriculture. 2007. Manitoba soil fertility guide. [Online]. Available from: www.gov.mb.ca/agriculture/crops/soil-fertility/soil-fertility-guide/pubs/soil_fertility_guide.pdf [5 Jun. 2019].

Metson, G.S., MacDonald, G.K., Haberman, D., Nesme, T., and Bennett, E.M. 2016. Feeding the corn belt: opportunities for phosphorus recycling in U.S. agriculture. Sci. Total Environ. **542**: 1117–1126. doi:10.1016/j.scitotenv.2015.08.047. PMID:26453407.

Möller, K., and Müller, T. 2012. Effects of anaerobic digestion on digestate nutrient availability and crop growth: a review. Eng. Life Sci. **12**: 242–257. doi:10.1002/elsc.201100085.

Möller, K., Oberson, A., Bünemann, E.K., Cooper, J., Friedel, J.K., Glæsner, N., et al. 2018. Improved phosphorus recycling in organic farming: navigating between constraints. Adv. Agron. **147**: 159–237.

Nesme, T., Metson, G.S., and Bennett, E.M. 2018. Global phosphorus flows through agricultural trade. Glob. Environ. Chang. **50**: 133–141. doi:10.1016/j.gloenvcha.2018.04.004.

Nicksy, J. 2021. Circular nutrients for supplying phosphorus and closing urban to rural nutrient cycles in organically managed cropping systems, M.Sc. thesis. University of Manitoba.

Nicksy, J., Amiro, B., and Entz, M. 2021. Recycled nutrients supply phosphorus and improve ryegrass yields on phosphorus depleted soil. Can. J. Soil Sci. doi:10.1139/cjss-2021-0004.

Nkoa, R. 2014. Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: a review. Agron. Sustain. Dev. **34**: 473–492. doi:10.1007/s13593-013-0196-z.

Organic Federation of Canada. 2020. September 10. Countdown to the publication of the 2020 Canadian Organic Standards. [Online]. Available from: www.organicfederation.ca/sites/documents/200909Infobio struviteenglg.pdf [2 Dec. 2020].

Pastor, B., Velasquez, Y., Gobbi, P., and Rojo, S. 2015. Conversion of organic wastes into fly larval biomass: bottlenecks and challenges. J. Insects Food Feed, **1**: 179–193. doi:10.3920/JIFF2014.0024.

Reimer, M., Hartmann, T.E., Oelofse, M., Magid, J., Bünemann, E.K., and Möller, K. 2020. Reliance on biological nitrogen fixation depletes soil phosphorus and potassium reserves. Nutr. Cycl. Agroecosyst. **118**: 273–291. doi:10.1007/s10705-020-10101-w.

Ross, C.-L., Mundschenk, E., Wilken, V., Sensel-Gunke, K., and Ellmer, F. 2018. Biowaste digestates: Influence of pelletization on nutrient release and early plant development of oats. Waste Biomass Valoriz. **9**: 335–341. doi:10.1007/s12649-016-9794-8.

Salvano, E., Flaten, D.N., Rousseau, A.N., and Quilbe, R. 2009. Are current phosphorus risk indicators useful to predict the quality of surface waters in Southern Manitoba, Canada? J. Environ. Qual. **38**: 2096–2105. doi:10.2134/jeq2008.0159. PMID:19704152.

Schindler, D.W., Hecky, R.E., and McCullough, G.K. 2012. The rapid eutrophication of Lake Winnipeg: greening under global change. J. Great Lakes Res. **38**: 6–13. doi:10.1016/j.jglr.2012.04.003.

Setti, L., Francia, E., Pulvirenti, A., Gigliano, S., Zaccardelli, M., Pane, C., et al. 2019. Use of black soldier fly (*Hermetia illucens* (L.), Diptera: Stratiomyidae) larvae processing residue in peat-based growing media. Waste Manag. **95**: 278–288. doi:10.1016/j.wasman.2019.06.017. PMID:31351613.

Sharpley, A., Jarvie, H., Flaten, D., and Kleinman, P. 2018. Celebrating the 350th anniversary of phosphorus discovery: a conundrum of deficiency and excess. J. Environ. Qual. **47**: 774. doi:10.2134/jeq2018.05.0170. PMID:30025053.

Sharpley, A., and Moyer, B. 2000. Phosphorus forms in manure and compost and their release during simulated rainfall. J. Environ. Qual. **29**: 1462–1469. doi:10.2134/jeq2000.00472425002900050012x.

Statistics Canada. 2016. Table 32-10-0406-01 land use.

Statistics Canada. 2017. Census profile, 2016 census. [Online]. Available from: https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/details/page.cfm?Lang=E&Geo1=PR&Code1=01&Geo2=&Code2=&SearchText=Canada&Search

Type=Begins&SearchPR=01&B1=All&TABID=1&type=0 [13 Mar. 2020].

Statistics Canada. 2021*a*. Table 32-10-0037-01 Canadian fertilizer production, by product type and fertilizer year, cumulative data (x 1,000). [Online]. Available from: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210003701 [3 Feb. 2021].

Statistics Canada. 2021*b*. Table 32-10-0038-01 Fertilizer shipments to Canadian agriculture and export markets, by product type and fertilizer year, cumulative data (x 1,000). [Online]. Available from: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210003801%09%09 [3 Feb. 2021].

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., et al. 2015. Planetary boundaries: guiding human development on a changing planet. Science, **347**: 1259855. doi:10.1126/science.1259855. PMID:25592418.

Talboys, P.J., Heppell, J., Roose, T., Healey, J.R., Jones, D.L., and Withers, P.J.A. 2016. Struvite: a slow-release fertiliser for sustainable phosphorus management? Plant Soil, **401**: 109–123. doi:10.1007/s11104-015-2747-3. PMID:27429478.

Tiessen, K.H.D., Elliott, J.A., Yarotski, J., Lobb, D.A., Flaten, D.N., and Glozier, N.E. 2010. Conventional and conservation tillage: influence on seasonal runoff, sediment, and nutrient losses in the Canadian Prairies. J. Environ. Qual. **39**: 964–980. doi:10.2134/jeq2009.0219. PMID:20400592.

Torri, S.I., Corrêa, R.S., and Renella, G. 2017. Biosolid application to agricultural land — a contribution to global phosphorus recycle: a review. Pedosphere, **27**: 1–16. doi:10.1016/S1002-0160(15)60106-0.

Wainaina, S., Awasthi, M.K., Sarsaiya, S., Chen, H., Singh, E., Kumar, A., et al. 2020. Resource recovery and circular economy from organic solid waste using aerobic and anaerobic digestion technologies. Bioresour. Technol. **301**: 122778. doi:10.1016/j.biortech.2020.122778. PMID:31983580.

Wegier, A., Alavez, V., Pérez-López, J., Calzada, L., and Cerritos, R. 2018. Beef or grasshopper hamburgers: the ecological implications of choosing one over the other. Basic Appl. Ecol. **26**: 89–100. doi:10.1016/j.baae.2017.09.004.

Welsh, C., Tenuta, M., Flaten, D.N., Thiessen-Martens, J.R., and Entz, M.H. 2009. High yielding organic crop management decreases plant-available but not recalcitrant soil phosphorus. Agron. J. **101**: 1027–1035. doi:10.2134/agronj2009.0043.

Wyngaarden, S.L., Lightburn, K.K., and Martin, R.C. 2020. Optimizing livestock feed provision to improve the efficiency of the agri-food system. Agroecol. Sustain. Food Syst. **44**: 188–214. doi:10.1080/21683565.2019.1633455.

Published by Canadian Science Publishing