Supplementary Information:
Mapping of phosphorus flows and analysis of the potential for recovery and reuse in Ontario, Canada

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Contents

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S1. Estimation of phosphorus flows

S1.1. Agriculture and aquaculture sector

Phosphorus flows in the agricultural sector are estimated based on production data of livestock and crop products, as well as on fertilizer application data.

Phosphorus in livestock feeding and manure is estimated based on the number and type of animals reported for Ontario in the Census of Agriculture, including cattle (Statistics Canada – Statistique Canada, 2021a), swine (Statistics Canada – Statistique Canada, 2021e), poultry (Statistics Canada – Statistique Canada, 2021f), and other livestock (Statistics Canada – Statistique Canada, 2021g,d), multiplied by the phosphorus feeding requirements and concentration of phosphorus in manure (Statistics Netherlands, 2012; Brown, Christine, 2013; Van Staden et al., 2021). We assumed that the number of animals reported is throughout the year (i.e., the animals culled are replaced by new ones). However, in the case of broilers and turkeys, the number of animals reported by the livestock census have been reduced by a factor of 0.68 (broilers) and 0.80 (turkeys), since these animals have life cycles of 43 and 80 days respectively, meaning barns are empty for 20 days between cycles (Yang et al., 2007).

Phosphorus flows through the imports and exports of animals are estimated using data on animal imports and exports (Statistics Canada – Statistique Canada, 2021b,c,h) multiplied by their phosphorus to live weight ratios (Statistics Netherlands, 2012).

Phosphorus contained in meat and slaughterhouse waste is based on the number of animals slaughtered reported by both federally and provincially licensed meat plants (Agriculture and Agri-Food Canada, 2021b,a) multiplied by the concentration of phosphorus in carcasses (Agriculture and Agri-Food Canada, 2021c; Hayse and Marion, 1973; Brake et al., 1995; Statistics Netherlands, 2012).

Phosphorus flows associated with the production of milk and eggs are based on provincial production data (Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs, 2020a,b), multiplying these products by their average phosphorus concentration (Health Canada, 2008; Chambers et al., 2017).

Phosphorus applied to open fields as synthetic fertilizer is estimated based on the amount of fertilizer products traded to Ontario's agricultural markets containing phosphorus (Statistics Canada – Statistique Canada, 2022). Regarding manure, we assume that all of the manure generated by livestock is applied in crop fields (van Bochove et al., 2010).

The uptake of phosphorus by crops is determined based on the area used in each census division (Opendatasoft, 2019) to grow each type of crops by census division (Agriculture and Agri-Food Canada, 2022a,b,c) multiplied by the specific yield and phosphorus content for each crop type (United States Department of Agriculture, 2009). The phosphorus uptake by crops is divided according to whether it is taken up in the grain, fruit or vegetable, or straw and stover components of each type of crop. This is necessary to determine the amount of phosphorus that flows within food or feed (i.e., grains, fruits and vegetables), while straw and stover remain in the field after harvesting as crop residues.

A fraction of the phosphorus applied to crop fields as manure or synthetic fertilizer is lost through erosion, runoff, and drainage. The magnitude of this flow depends on a range of factors, including the amount of phosphorus applied; soil composition, texture, and slope; and precipitations, resulting in a complex and data-intensive process for estimating the phosphorus transported out of the crop fields. As an approximation, we have estimated the phosphorus losses by using export coefficients determined for crop fields in Ontario corrected to account for both surface and subsurface runoffs for synthetic fertilizers (1.267 kg/ha/year), and liquid and solid manure (2.548 kg/ha/year and 1.717 kg/ha/year respectively) (Zhang et al., 2015; Wang et al., 2018; Tan and Zhang, 2011). In addition, a fraction of the P supplied to crop fields is not taken up by the plants and remains in soil, resulting in the accumulation of P over time as a result of synthetic fertilizer and manure over sustained periods of time, often applying phosphorus in greater quantities than crops require to ensure satisfactory yields (Reid et al., 2019). This buildup is often referred to as "legacy P", and it is estimated as the balance between phosphorus inflows to crop fields (application of manure and synthetic fertilizers) and outflows (crop food and feed products, crop residues, and phosphorus losses by erosion and runoff).

Regarding greenhouse crops, the data available was limited, resulting in an estimation of phosphorus applied as synthetic fertilizers based on the sum of phosphorus uptake by greenhouse crops and phosphorus releases from greenhouse irrigation systems also known as greenhouse nutrient feedwater (GNF) systems (Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs, 2021). The phosphorus uptake by greenhouse crops is determined by multiplying the production of greenhouse crops (Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs, 2022) by the phosphorus content of each vegetable type (United States Department of Agriculture, 2009). The phosphorus releases from the GNF systems were estimated based on the average concentration of phosphorus in GNF outlet streams for Ontario, 33.6 mg/L (Ontario Ministry of the Environment, Conservation and Parks, 2012), and the total water discharges from GNF systems, assuming that the water discharges are equivalent to 25% of the total water applied in greenhouses, which corresponds with the worst-case scenario of no water recirculation in the GNF systems (Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs, 2021). The average water consumption in greenhouses in Ontario was assumed to be 1,000 L/m^2/year (Ontario Ministry of Agriculture and Food and the Ministry of Rural Affairs, 2011). We have also estimated the phosphorus releases from the seasonal workers living in households in the vicinity of the greenhouses that may use septic systems, considering that the seasonal labour force in Ontario greenhouses is estimated to be 6,699 workers (Government of Canada, 2022), and an average phosphorus load rate of 0.0156 kg P/person/week from septic systems (Oldfield et al., 2020).

Phosphorus enters aquaculture systems as fish feed, primarily in the growth of trouts. A fraction of this phosphorus goes to the fish and the remainder is discharged into aquatic ecosystems as aquaculture effluents (Ontario Ministry of the Environment, Conservation and Parks, 2019). The total phosphorus in fish produced in Ontario is calculated by multiplying the fish production (Statistics Canada - Statisque Canada, 2021) by their phosphorus content (Health Canada, 202), while the phosphorus content in the aquaculture waste effluents of Ontario is estimated to be 10 kg of phosphorus per ton of fish produced (Bureau et al., 2003). The phosphorus in Ontario fish feed that is supplied to aquaculture, is estimated to be the sum of the phosphorus in the fish produced and the phosphorus in aquaculture effluent.

S1.2. Industrial sector

Phosphorus flows through imports, production, exports and waste for the food, steel, and forestry industries of Ontario were mapped.

Processed food imports and exports are estimated scaling each type of food traded in Canada (Statistics Canada - Statisque Canada, 2022c) with the population of Ontario (Statistics Canada - Statisque Canada, 2022b). The phosphorus contained in each type of imported and exported food is estimated by multiplying the amount of each type of traded food by its phosphorus content (Health Canada, 202). Phosphorus flows in the form of food and organic waste are based on applying food loss factors for the steps associated with food processing, from the production of food raw materials to consumption (FAO, 2011), considering the food production and import values estimated in Section S1.1.

The steel industry is the first non-food sector in terms of phosphorus use. The main phosphorus inflows of steel manufacturing are associated with the use of iron ore, coal, and coke, while the main outflow of phosphorus is within slag, a by-product of steelmaking. During steelmaking, most of the impurities, including phosphorus, separate into the slag phase. It must be noted that, although some minor amounts of phosphorus can be desired in steel for making anti-corrosion surface coatings, it is largely considered an impurity in the steel manufacturing process. Phosphorus in these flows is estimated by multiplying their average phosphorus content (0.06% P in iron ore, 0.05% P for coal, 0.4% P in slag, and 0.01% in steel) (Yokoyama et al., 2007) by the steel production capacity of the facilities located in Ontario (Cheminfo Services Inc., 2019; Algoma Steel Inc., 2022; Stelco Inc., 2022; Pollution Probe, 2022) and the imports and exports of these materials (World Integrated Trade Solution, 2022; Statistics Canada - Statisque Canada, 2022a). The P in slag is estimated using component balancing.

Phosphorus flows in Ontario's forestry industry include wood harvesting, wood products manufacturing, as well as the production of pulp and paper. The estimation of these phosphorus flows are the result of multiplying the production data of wood, wood products, pulp and paper, and their respective imports, exports, and waste streams (Canadian Forest Service, 2020; Statistics Canada - Statisque Canada, 2022a), by their average phosphorus content. The average phosphorus content used for wood is 0.01% (Sardans and Peñuelas, 2013) and 0.005% is estimated for pulp and paper products, using component balancing.

The local production of phosphorus is assumed to be negligible since phosphorus is not mined or refined in Ontario. Synthetic phosphorus fertilizer and phosphorus chemical imports are estimated similar to food imports. The phosphorus fertilizer imports are accounted for in the agricultural section. Chemical facilities located in Ontario report 350 t/year of phosphorus as waste (Pollution Probe, 2022). However, a significant fraction of phosphorus used in the industrial sector cannot be tracked due to the lack of data.

S1.3. Slaughter industry

Table S1 collects the number of animals slaughtered and the phosphorus in slaughterhouse waste in the province of Ontario for year 2019.

Table S1: Truncated normal distribution fitting parameters for the distribution of cAFOs sizes in regions of the Great Lakes area.

<table>
<tr><th></th><th>Cattle</th><th>Swine</th><th>Sheep</th><th>Rabbit</th><th>Poultry</th><th>Total</th></tr>
<tr><td>Animals slaughtered in federally licensed facilities (heads, 2019)</td><td>628,366</td><td>4,010,926</td><td>84,721</td><td>Not available</td><td rowspan="2">238,979,246 (total)</td><td rowspan="2">244,663,410</td></tr>
<tr><td>Animals slaughtered in provincially licensed facilities (heads, 2019)</td><td>99,561</td><td>368,267</td><td>266,946</td><td>225,377</td></tr>
<tr><td>P flows through slaughterhouse waste in t (2019)</td><td>2,222</td><td>621</td><td>42</td><td>7.3</td><td>904</td><td>3,796.6</td></tr>
</table>

S2. Phosphorus recovery processes

S2.1. Scaling CAFOs phosphorus recovery processes

We refer the reader to Martín-Hernández et al. (2021) for a detailed description on estimating the phosphorus recovery costs of processes from phosphorus recovery from livestock facilities. Capital costs are annualized through the application of an annual capital charge ratio ($ACCR$) as defined by Towler and Sinnott (2013), shown in Eq. S1, assuming a typical interest rate i of 5% and a plant lifetime n of 20 years.

$$ACCR = \frac{i\,(1+i)^n}{(1+i)^n - 1} \tag{S1}$$

S2.2. Scaling municipal wastewater phosphorus recovery processes

Data on processes for phosphorus recovery from municipal wastewater is taken from Egle et al. (2016). We assume that, similarly to other industrial activities (Dysert and Pickett, 2005), the phosphorus recovery cost from municipal wastewater in function of the plant capacity shows an exponential behavior. In consequence, the cost-to-capacity method (Baumann, 2014) is used to estimate phosphorus recovery cost from municipal wastewater in function of the plant capacity, as shown in Eq. S2, where x denotes the scale factor 'facility 2' refers to the facility which cost is required while 'facility 1' denotes the facility whose data is known. The scale factor x is estimated based on the data for different capacities reported by Egle et al. (2016) through the transformation of Eq. S2 by applying natural logarithms to both sides of the equation, as shown in Eq. S3. The scale factor obtained are shown in Table S2. The capacity magnitude has been normalized to the mass of phosphorus recovered.

Table S2: Estimation of scale factors for municipal wastewater phosphorus recovery systems.

Inflow	Technology	Type	P recovery potential (% related to inflow)	P inflow (kg P/year)	Annual processing cost (EUR)	Scale factor x
WWTPs (liquid phase)	Crystalactor	Struvite/Calcium phosphate	38	65700 328500	305920 795893	0.59
	Ostara Pearl	Struvite	20	65700 328500	130856 235234	0.36
	P-RoC	Calcium phosphate	27	65700 328500	75970 266025	0.78
	REM-NUT	Struvite	47	65700 328500	977933 4417171	0.94
	AirPrex	Struvite	15	65700 328500	74195 137693	0.38
	PRISA	Struvite	18	65700 328500	186923 371578	0.43
WWTPs	Stuttgart process	Struvite	40	65700 328500	581730 2419407	0.89
	Gifhorn process	Struvite	40	65700 328500	400384 1491509	0.82
	PHOXNAN	Struvite	51	65700 328500	891667 3468902	0.84
	Aqua Reci	Calcium phosphate	61	65700 328500	939605 3529595	0.82
	MEPHREC	P rich slag	68	65700 657000	1154473 4715866	0.61

$$\frac{\text{Cost}_{\text{facilitiy 2}}}{\text{Cost}_{\text{facilitiy 1}}} = \left(\frac{\text{Capacity}_{\text{facilitiy 2}}}{\text{Capacity}_{\text{facilitiy 1}}}\right)^{x} \tag{S2}$$

$$x = \frac{\ln\left(\frac{\text{Cost}_{\text{facilitiy 2}}}{\text{Cost}_{\text{facilitiy 1}}}\right)}{\ln\left(\frac{\text{Capacity}_{\text{facilitiy 2}}}{\text{Capacity}_{\text{facilitiy 1}}}\right)} \tag{S3}$$

S2.3. Phosphorus recovery technologies techno-economic data

Table S3 collects the main specifications of the phosphorus recovery technologies considered in this work, including the estimation of phosphorus recovery cost.

Table S3: Phosphorus recovery technologies considered in the study. For the treatment of manure we assumed that the units for the separation of the solid and liquid phases is already implemented in the livestock operations. F denotes the phosphorus recovered as $\text{kg P}_{\text{recovered}}/\text{year}$, while $\lceil x \rceil$ represent the ceiling function applied to x. The definition of annual capital charge ratio ($ACCR$) can be found in the Supplementary Material, Section 1.1. Refs: 1: Martín-Hernández et al. (2021), 2: Jupp et al. (2021), 3: Egle et al. (2016), 4: Schoumans et al. (2010), 5: Szögi et al. (2008), 6: AMPC (2018), 7: Zagklis et al. (2020), 8: Fernández-Delgado et al. (2022), 9: Ohtake and Tsuneda (2019), 10: Sharma and Chandel (2021)

Sector	Inflow	Pretreatment	Pretreatment cost (EUR/kg $P_{\text{recovered}}$)	Technology	Type	P recovery potential (% related to inflow)	P recovery cost (EUR/kg P recovered)	TRL	Ref tech
Agriculture	Cattle and swine manure, liquid phase (30% of total manure P)	Solid-liquid separation	-	Multiform	Struvite	60	$25.7 + 1.10 \cdot 10^6 \cdot \lceil 1.19 \cdot 10^{-4} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[1]
		Solid-liquid separation	-	Crystalactor	Struvite/ calcium phosphate	60	$3.53 + \left(2.30 \cdot 10^6 + 0.71 \cdot \lceil 3.32 \cdot 10^{-5} \cdot F \rceil\right) \lceil 3.32 \cdot 10^{-5} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[1]
		Solid-liquid separation	-	Ostara Pearl 500	Struvite	60	$12.57 + 2.30 \cdot 10^6 \cdot \lceil 7.02 \cdot 10^{-5} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[1]
		Solid-liquid separation	-	Ostara Pearl 2K	Struvite	60	$12.57 + 3.10 \cdot 10^6 \cdot \lceil 1.83 \cdot 10^{-5} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[1]
		Solid-liquid separation	-	Ostara Pearl 10K	Struvite	60	$12.57 + 10.00 \cdot 10^6 \cdot \lceil 3.65 \cdot 10^{-6} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[1]
		Solid-liquid separation	-	Nuresys	Struvite	60	$10.37 + 1.38 \cdot 10^6 \cdot \lceil 2.24 \cdot 10^{-5} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[1]
		Solid-liquid separation	-	MAPHEX	Solid	90	$184.67 + 0.30 \cdot 10^6 \cdot \lceil 2.47 \cdot 10^{-4} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	6	[1]
	Cattle and swine manure, solid phase (70% of total manure P)	Incineration	8.9	EcoPhos	Phosphoric acid	82	4.5	6	[2,3,4]
		Incineration	8.9	AshDec depollution	Calcium phosphate	86	1.8	6	[2,3,4]
		Incineration	8.9	AshDec Rhenania	Calcium phosphate	86	1.9	6	[2,3,4]
		Incineration	8.9	PASCH	Calcium phosphate	79	4.7	6	[2,3,4]
		Incineration	8.9	LEACHPHOS	Calcium phosphate	78	5.1	9	[2,3,4]
		Incineration	8.9	RecoPhos	Mineral	87	2.5	9	[2,3,4]
		Incineration	8.9	Thermophos	P4	81	2.7	9	[2,3,4]
	Poultry litter	-	-	Quick wash	Solid precipitate	70	4.4	4-6	[5]
	Slaughterhouse waste, liquid phase (14% of total slaughterhouse P)	-	-	Multiform	Struvite	84	$22.6 + 1.10 \cdot 10^6 \cdot \lceil 1.05 \cdot 10^{-4} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[6]
		-	-	Ostara Pearl 500	Struvite	58	$15.60 + 2.30 \cdot 10^6 \cdot \lceil 8.70 \cdot 10^{-5} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[6]
		-	-	Ostara Pearl 2K	Struvite	58	$15.60 + 3.10 \cdot 10^6 \cdot \lceil 2.26 \cdot 10^{-5} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[6]
		-	-	Ostara Pearl 10K	Struvite	58	$15.60 + 10.00 \cdot 10^6 \cdot \lceil 4.53 \cdot 10^{-6} \cdot F \rceil \cdot ACCR \cdot \frac{1}{F}$	9	[6]
	Slaughterhouse waste, solid phase (86% of total slaughterhouse P)	Incineration	14.6	EcoPhos	Phosphoric acid	82	4.5	6	[2,3,7]
		Incineration	14.6	AshDec depollution	Calcium phosphate	86	1.8	6	[2,3,7]
		Incineration	14.6	AshDec Rhenania	Calcium phosphate	86	1.9	6	[2,3,7]
		Incineration	14.6	PASCH	Calcium phosphate	79	4.7	6	[2,3,7]
		Incineration	14.6	LEACHPHOS	Calcium phosphate	78	5.1	9	[2,3,7]
		Incineration	14.6	RecoPhos	Mineral	87	2.5	9	[2,3,7]
		Incineration	14.6	Thermophos	P4	81	2.7	9	[2,3,7]
Urban & industrial	WWTPs (liquid phase, 14% of total wastewater P)	-	-	Crystalactor	Struvite/ Calcium phosphate	38	$305,920 \cdot \left(\frac{F}{24,966}\right)^{0.59} \cdot \frac{1}{F}$	9	[3]
		-	-	Ostara Pearl	Struvite	20	$130,856 \cdot \left(\frac{F}{13,140}\right)^{0.36} \cdot \frac{1}{F}$	9	[3]
		-	-	P-RoC	Calcium phosphate	27	$75,970 \cdot \left(\frac{F}{17,739}\right)^{0.78} \cdot \frac{1}{F}$	6	[3]
		-	-	REM-NUT	Struvite	47	$977,933 \cdot \left(\frac{F}{30,879}\right)^{0.94} \cdot \frac{1}{F}$	6	[3]
		-	-	AirPrex	Struvite	15	$74,195 \cdot \left(\frac{F}{9,855}\right)^{0.38} \cdot \frac{1}{F}$	9	[3]
		-	-	PRISA	Struvite	18	$186,923 \cdot \left(\frac{F}{11,826}\right)^{0.43} \cdot \frac{1}{F}$	6	[3]
	WWTPs (sewage sludge, 86% of total wastewater P)	-	-	Stuttgart process	Struvite	40	$581,730 \cdot \left(\frac{F}{26,280}\right)^{0.89} \cdot \frac{1}{F}$	9	[3]
		-	-	Gifhorn process	Struvite	40	$400,384 \cdot \left(\frac{F}{26,280}\right)^{0.82} \cdot \frac{1}{F}$	9	[3]
		-	-	PHOXNAN	Struvite	51	$891,667 \cdot \left(\frac{F}{33,507}\right)^{0.84} \cdot \frac{1}{F}$	6	[3]
		-	-	Aqua Reci	Calcium phosphate	61	$939,605 \cdot \left(\frac{F}{40,077}\right)^{0.82} \cdot \frac{1}{F}$	6	[3]
		-	-	MEPHREC	P rich slag	68	$1,154,473 \cdot \left(\frac{F}{44,676}\right)^{0.61} \cdot \frac{1}{F}$	6	[3]
	WWTPs (sewage sludge ash SSA, 86% of total wastewater P)	Incineration	8	EcoPhos	Phosphoric acid	82	4.5	6	[3]
		Incineration	8	AshDec depollution	Calcium phosphate	86	1.8	6	[3]
		Incineration	8	AshDec Rhenania	Calcium phosphate	86	1.9	6	[3]
		Incineration	8	PASCH	Calcium phosphate	79	4.7	6	[3]
		Incineration	8	LEACHPHOS	Calcium phosphate	78	5.1	9	[3]
		Incineration	8	RecoPhos	Mineral	87	2.5	9	[3]
		Incineration	8	Thermophos	P4	81	2.7	9	[3]
	Organic municipal separation & food waste	Incineration	6.43	AshDec Rhenania	Calcium phosphate	86	1.9	6	[3,9,10]
		Incineration	6.43	PASCH	Calcium phosphate	79	4.7	6	[3,9,10]
		Incineration	6.43	LEACHPHOS	Calcium phosphate	78	5.1	9	[3,9,10]
		Incineration	6.43	RecoPhos	Mineral	87	2.5	9	[3,9,10]
		Incineration	6.43	Thermophos	P4	81	2.7	9	[3,9,10]

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