Phosphorus in Ontario's economic sectors: mapping flows and assessing recovery and recycling potential

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Abstract

The dual dimension of the anthropogenic use of phosphorus, i.e., its key role in the food production system and the negative environmental impacts associated with the phosphorus used in intensive agricultural techniques, has been stated by the United Nations Environment Assembly. In addition, phosphorus is a non-renewable material which reserves are concentrated in a few number of regions, making global supply chains vulnerable to regional events and conflicts. As a consequence, the recovery and recycling of phosphorus is not just a desirable but also a necessary approach to assure a sustainable, reliable, and sovereign food production system. In this work we map the phosphorus flows through the economic sectors of the Canadian province of Ontario, and phosphorus recovery and recycling opportunities are identified. These mainly belong to the agricultural sector, including manure (30.5 kt/year) and slaughterhouse waste (3.7 kt/year), although significant amounts of P are also found in food and organic waste, including municipal wastewater (6.4 kt/year). Different scenarios are studied to determine the amount of phosphorus that could be recovered within the province considering according with the technology readiness level of different phosphorus recovery processes, as well as the costs associated with phosphorus recovery Add some more numbers here. Finally, we discuss the implications that would be derived from implementing active phosphorus recovery and recycling approaches regarding phosphorus supply and use in Ontario.

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1. Introduction

Phosphorus is an essential for production of food which has been intensively used for crop and livestock production since the development of synthetic fertilizers in the XIX and XX centuries (Samreen and Kausar, 2019). The combination of synthetic fertilizers with other modern intensive agricultural techniques have increased the productivity of agriculture and farming industries (Pingali, 2012). However, the intensive use of fertilizers in agriculture has resulted in the over-application of phosphorus in many regions worldwide REF, while the run of intensive livestock production facilities, also known as concentrated animal feeding operations (CAFOs) (U.S. Department of Agriculture, 2011), result in important difficulties in the management of the large amounts of manure produced, which is often spread in lands in the vicinity of CAFOs, which also leads to the accumulation of phosphorus in soil. Soil acts as a phosphorus reservoir (Ehlert et al., 2003), building-up a legacy P that can be used for future crops, but also can be transported to waterbodies by erosion and runoff leading to the eutrophication of aquatic ecosystems.

The dual dimension of the anthropogenic use of phosphorus, i.e., its key role in the food production system and the negative environmental impacts associated with the phosphorus used in intensive agricultural techniques, has been stated by the United Nations Environment Assembly in the resolution UNEP/EA.5/Res.2 (United Nations Environment Programme, 2022). An additional factor to be considered for addressing the phosphorus challenge is the non-renewable nature of phosphorus, since the phosphorus consumed is not replenished by natural means at human time scale, and there is currently no known synthetic substitute for this material (Cordell et al., 2009). Since the global phosphorus reserves are concentrated in a few number of regions, the supply of phosphorus from a limited number of global supply chains lacks resiliency and it has been proven that it can be globally disrupted by regional events and conflicts, resulting geopolitical tensions (Food and Agriculture Organization of the United Nations, 2022). As a consequence, the recovery and recycling of phosphorus is not just a desirable but also a necessary approach to assure a sustainable, reliable, and sovereign food production system.

Although the main uses of phosphorus are in the agri-food sector, phosphorus is also involved in other industrial activities, including steel, chemical, and forestry industries. Henceforth, phosphorus is a key material for many aspects of human development. As a result, mapping the phosphorus flows involved in human activities to detect opportunities for recovery and recycling is essential for, in a second stage, assess amount of phosphorus that is viable to recover, the economical costs involved, and the enhancement in terms of resiliency of the regional food production system, savings from the reduction of phosphorus imports, and the mitigation of phosphorus pollution on the region implementing strategies for phosphorus recovery and recycling. The quantification of phosphorus flows has been addressed in previous works in the literature for certain sectors such as the agri-food sector (Boh and Clark, 2020; Zhou et al., 2021; Nesme et al., 2018). Additionally, studies on the global phosphorus flows have also been performed (Villalba et al., 2008; Chen and Graedel, 2016), although these studies tend to have a low flow resolution since these are aggregated by major sectors. Additionally, the works quantifying phosphorus often include qualitative recommendations to improve the phosphorus use efficiency and recycling (Van Dijk et al., 2016; Senthilkumar et al., 2012), but often they do not include quantitivae assessments on the amount of phopshorus which recovery is feasible along with the costs involved. Conversely, those works focused on estimating the recoverable phosphorus and the associated recovery cost target specific flows, lacking a holistic perspective of the phosphorus flows in the various human activities (Martín-Hernández et al., 2021; Sampat et al., 2018).

In this work, we intend to perform a holistic approach to the opportunities for phosphorus recovery and recycling in the Canadian province of Ontario. In a first stage, we proceed to ma the phosphorus flows involved in the economical sectors of Ontario, i.e., the agri-food, industrial, and urban sectors. This data is used in a second stage to identify the flows in which phosphorus recovery is feasible, determining the amount of phosphorus that could be recovered within the province considering different scenarios regarding the technology readiness level of different phosphorus recovery processes, as well as the costs associated with phosphorus recovery. Finally, we discuss the implications that would be derived from implementing active phosphorus recovery and recycling approaches regarding phosphorus supply and use in Ontario.

2. Methods

2.1. Spatial resolution

Phosphorus flows have been mapped within the Canadian province of Ontario, and thus the political borders of Ontario has been considered as the boundaries for the substance flow analysis performed. In those cases where the data was availbale, the distribution of phosphorus flows within Ontario has also been studied at Census Division level (Statistics Canada – Statistique Canada, 2017). The database collecting the IDs of Ontario Census Divisions, their names, and geospatial information is taken from Opendatasoft (2019).

ADD MAP WITH CENSUS DIVISIONS????

2.2. Temporal resolution

The study has being performed for year 2019 since the most of data required is available for this year. In addition, the temporal evolution of the largest phosphorus flows, i.e., agricultural and wastewater phosphorus flows, has been studied for a period of 13 years from 2007 to 2019.

2.3. Estimation of phosphorus flows

The estimation of phosphorus flows within the Ontario's agricultural sectors is based on the methodology used in Pollution Probe (2022). It is based on the use open data sources, often from governmental institutions, complemented with information from scientific articles when needed. The particular procedure followed for each flow depends on the information publicly available. In the next sections we depict the main lines of the estimating procedure for each sector, while we refer the reader to Pollution Probe (2022) for a more comprehensive description of the procedure followed for estimating each phosphorus flow.

2.3.1. Agricultural sector

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

For those production data were not available, a number of different methods were used to estimate the P flow based on approaches established in the literature. For example, P inflows associated with synthetic fertilizers could be directly estimated based on application data reported in the Fertilizer Shipments Survey (FSS).37 Conversely, P flows associated with manure were determined indirectly by accounting for the magnitude from which the flow of P could be derived. In this case,

Phosphorus in livestock imports and exports is estimated from livestock trading data REF, multiplying the number of animals by the concentration of phosphorus in the different types of livestock REF,

Phosphorus in livestock feeding and manure is estimated based on the number and type of animals reported for Ontario at Census Division level in the Census of Agriculture REF!, multiplied by the phosphorus feeding requirements REF, and concentration of phosphorus in manure REF. The Census of Agriculture is published by Statistics Canada every five years (i.e., 2001, 2006, 2011, and 2016) for cattle52 REF, sheep53 REF, swine54 REF, poultry55 REF, and other livestock56 REF, with the exception of rabbits, where data is not available prior to 2009. The number of animals for the years in between census reporting have been estimated using a linear interpolation. 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. 305 REF

Phosphorus contained in meat and slaughterhouse waste is based on the number of animals slaughtered reported by both federally and provincially licensed meat plants.59, 60 REF multiplied by the concentration of phosphorus in carcasses REF.

Phosphorus flows associated with the production of milk and eggs is based on provincial production data, multiplying these products by their average phosphorus concentration 57, 58 REF.

Phosphorus in fertilizer applied to open fields in Ontario is estimated based on the amount of fertilizer products traded to Ontario's agricultural markets containing P 100 REF. The distribution of phosphorus fertilizers among the Census Division of the province is based on the fraction of fertilized area of each census division, i.e., dividing the reported area of land fertilized for each census division by the total fertilized area of land in Ontario, removing the areas that correspond with greenhouse crops101, 102 103 REF. Regarding manure, we assume that all of the manure generated by livestock is applied in crop fields 50 REF.

The uptake of phosphorus by crops is determined based on the area used in each Census Division to grow each type of crops by census division104, 105, 106 and its yield107, 108 multiplied by the specific P content for each crop type.109, 110. The phosphorus uptake by crops is divided according to whether it uptake 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 of synthetic fertilizer is lost through erosion, runoff, and drainage. This transportation of phosphorus depends on a range of factor, including the amount of phosphorus applied; soil composition, texture, and slope; and precipitation, 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 112 REF 113 REF 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) 113 REF (Pollution Probe, 2022).

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 over sustained periods of time, often applying phosphorus in greater quantities than crops require to ensure satisfactory yields 132 REF. 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).

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 (i.e., tomatoes, peppers, and cucumbers)119 and the phosphorus releases from greenhouse irrigation systems (greenhouse nutrient feedwater systems (GNF) REF ONTARIO) systems. The phosphorus uptake by greenhouse crops is determined by multiplying the production of greenhouse crops 120 REF by the phosphorus content of each vegetable type 121, 122 REF. The phosphorus releases from the GNF systems was estimated based on the average concentration of phosphorus in GNF outlet streams of Ontario (33.6 mg/L) 123 REF and the total water discharges from GNF systems 124 REF, assuming that water discharges from GNF systems is equivalent to 25% of the total water applied in greenhouses, which corresponding with the worst-case scenario of no water recirculation in the GNF system. The average water consumption in greenhouses in Ontario was assumed to be 1,000 L/m2/year 125 REF. We have also estimated the phosphorus releases from the seasonal workers live 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 126 REF, and an average phosphorus load rate of f 0.0156 kg P/person/week from septic systems 128 REF.

REVISAR POR SIDNEY Food imports and exports (other than livestock) 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 multiplying the amount of ech type of traded food by its phosphorus content (Health Canada, 202).

2.3.2. Industrial sector

Phosphorus flows through imports, production, exports and waste for the steel, forestry, and food and beverage, industries of Ontario were mapped. 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, which remove most of the impurities from steel, including phosphorus. It must be noted that, although some minor amounts of phophosphorus 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 multiplyting 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) 176 REF 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).

Phosphorus flows in Ontario's forestry industry includes 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 retrospectives imports, exports, and waste streams (Canadian Forest Service, 2020; Statistics Canada - Statisque Canada, 2022a), by the average phosphorus content, which is assumed to be 0.01% for wood 181 REF and 0.005% for pulp and paper products REF.

Phosphorus in aquaculture are mainly due to supply of feed as part of fish feed the grow of trouts, part of which is uptake by fishes, while the rest of phosphorus is released into aquatic ecosystems since aquaculture effluents are directly discharged to the environment (Ontario Ministry of the Environment, Conservation and Parks, 2019). The amount phosphorus uptakes by fishes is calculated 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 sum of phosphorus uptakes by fishes and phosphorus in aquaculture waste effluents result in the phosphorus supplied to aquaculture as fish feed.

Regarding other industrial activities which could involve the use of phosphorus, the local production of phosphorus is assumed to be negligible since phosphorus is not mined or refined in Ontario, and the synthetic phosphorus fertilizer imports are accounted in the agricultural section. The general chemical facilities located in Ontario report 350 t/year of phosphorus as waste REF, in addition of imports and exports of chemical products REF. However, there exist a significant fraction of phosphorus used in the industrial sector that cannot be tracked due to the lack of data.

Ask sidney what to do with food industry, and pet feed. My approach is to merge all of them as it is currently in the figure, but confirm with her

2.3.3. Urban sector

In this section we include the phosphorus inflows and outflows through wastewater treatment plants (WWTPs), septic systems, and food and organic waste management facilities (landfills, composting sites, and anaerobic digestion facilities).

Jorge do you mind if the purposes of the papaer we stick with just one method? I think it is better, otherwise it becomes lengthy and confusing

Phosphorus flows through WWTPs is estimated combining data from the National Pollutant Release Inventory (NPRI) REF, a public database of releases, disposals and transfers of pollutants, including industrial facilities, and data from the Wastewater Systems Effluent Regulations (WSER) database REF. Since the NPRI only contains data of those facilities that meet certain regulatory requirements, the information of this database must be complemented with the data from the WSER database, which includes information of Canadian WWTPs at the federal, provincial, and municipal level. The estimations on phosphorus flows through WWTPs are valitaed using the Municipal Treated Wastewater Effluent (MTWE) database REF, which collects annual data on water quality data and effluent levels for WWTPs in Ontario. We note that this data set only provides information about phosphorus releases from municipal WWTPs, but it does not collect phosphorus disposals and transfers. REVISAR POR JORGE. This methodology is shown in Figure 1

Ask Jorge if I can make a new Figure

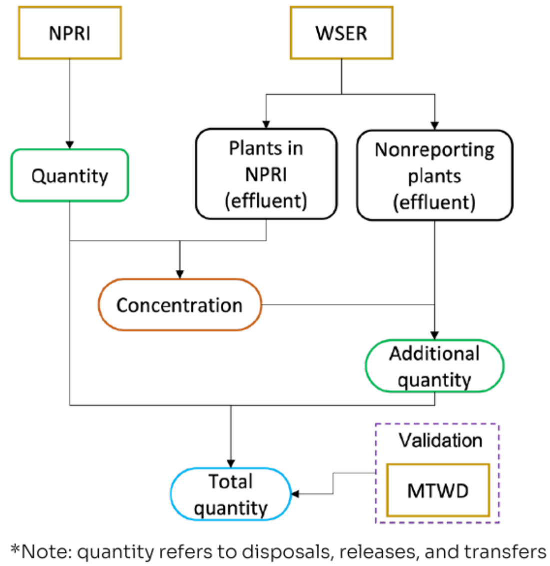


Figure 1: Methodology used for estimating phosphorus flows through wastewater treatment plants.

However, there exist households that are not connected to any sewer systems. These households are equipped with septic systems to perform a rough treatment of the wastewater produced prior to its release into the environment, which typically consist into a septic tank that separates solid matter from the wastewater, and a drainfield where the effluent is discharged. The estimation of phosphorus releases from septic systems is based on the fraction of households equipped with these systems, estimated on 13% (Statistics Canada - Statisque Canada, 2015), which are inhabited by an average of 2.58 individuals (Statistics Canada - Statisque Canada, 2017), and the average phosphorus load rate from septic systems, which is estimated on 0.81 kg of phosphor per person per year for the Lake Erie Basin in Ontario by Oldfield et al. (2020).

Phophorus flows in the form of food and organic waste are based on applying food loss factors for the steps associated with food processing (FAO, 2011), considering the food production and import values estimated in Section 2.3.1.

2.4. Phosphorus recovery techniques ***(This section could be Supplementary Material)***

Table ??? shows a summary of the specifications of phosphorus recovery technologies for different streams. These table is based on different processes at different development level, from commercial to pilot plant stages. A collection of phosphorus recovery technologies for different streams can be found in the Table ??? of the Supplementary Material. Different scenarios are studied considered the technology readiness level (TRL) of the processes in order to determine the phosphorus that could be immediately recovered using commercial technologies (Scenario 1), the phosphorus that could be recovered in a near future by using technologies above pilot plant development stage (Scenario 2), and finally prospective assessment of phosphorus recovery systems that at early research stages (Scenario 3).

Phosphorus recovery costs include operating and annualized capital costs. Capital costs are annualized through the application of an annual capital charge ratio ($ACCR$) as defined by Towler and Sinnott (2013), assuming a typical interest rate of 5% and a plant lifetime of 20 years. Dynamic phosphorus recovery costs in function of the processing capacity have been considered in order to capture the economies of scale for those technologies for which sufficient data are available.

3. Results and discussion

3.1. Phosphorus flows in Ontario

Showing an overview of the P flows in the province. The use of figures summarizing all the flows of the province in the shape of Sankey or network flow figures could be so great

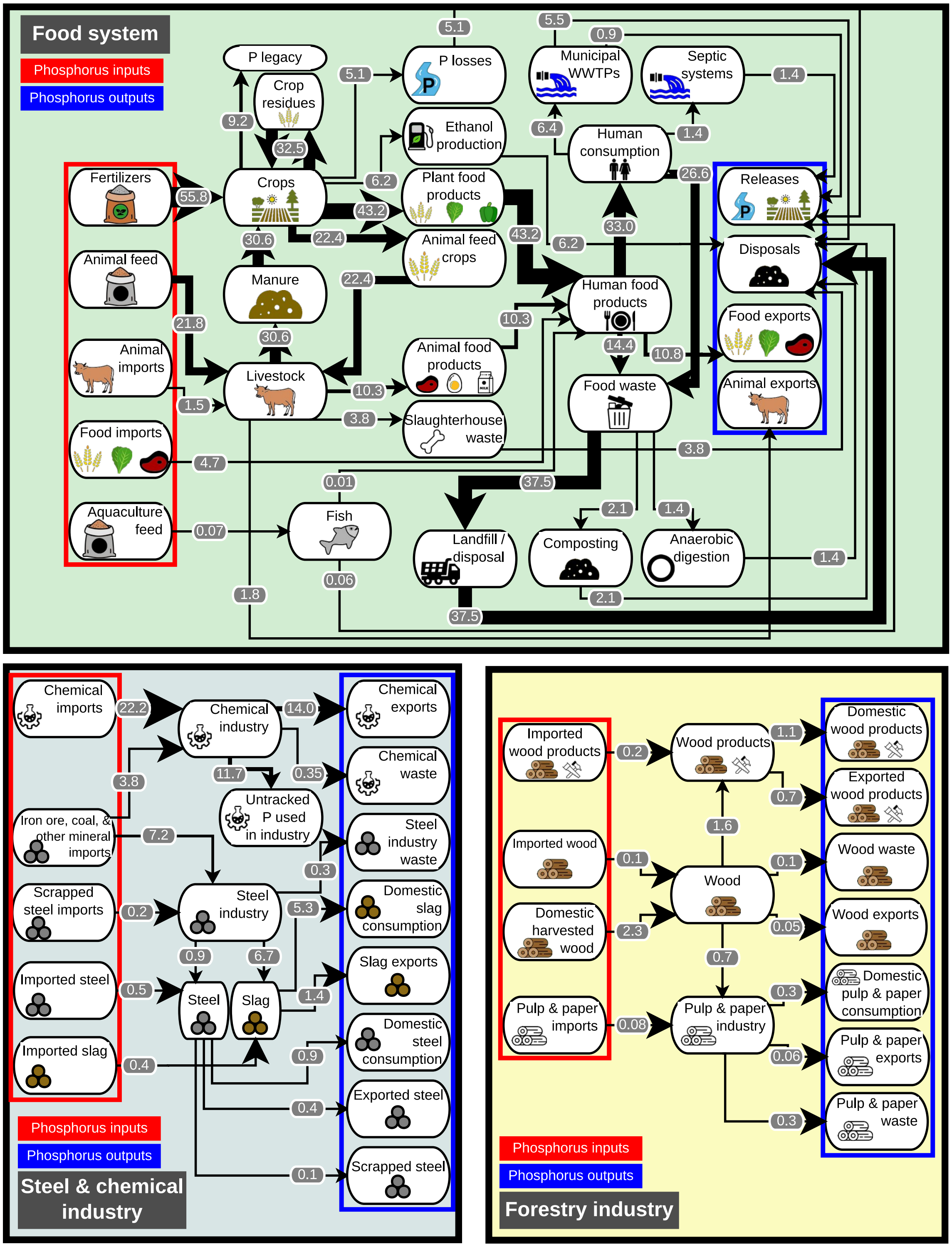


Figure 2: Phosphorus flows in the province of Ontario (kt/year). The streams within red rectangles denote phosphorus inflows into the province, while those streams within blue rectangles denote phosphorus outflows out of the province.

Figure 2 summarizes the phosphorus flows in the province of Ontario. It can be observed that the flow of of phosphorus through the anthropogenic activities are divided into 3 independent networks, i.e., the flow of phosphorus involved the production and processing of food (including the treatment of wastewater), the flow of phosphorus used in the steel and chemical industries, and the phosphorus involved in the forestry industry.

The production of animal food products exhibits a lower phosphorus use efficiency than the production of plant base products, similarly to the use effciciency of other resources such as water CITE HERE, CALCULAR ENTRA VS SALE!

3.1.1. Agricultural sector

3.1.2. Industrial sector

3.1.3. Urban sector

3.2. Potential of phosphorus recovery in Ontario

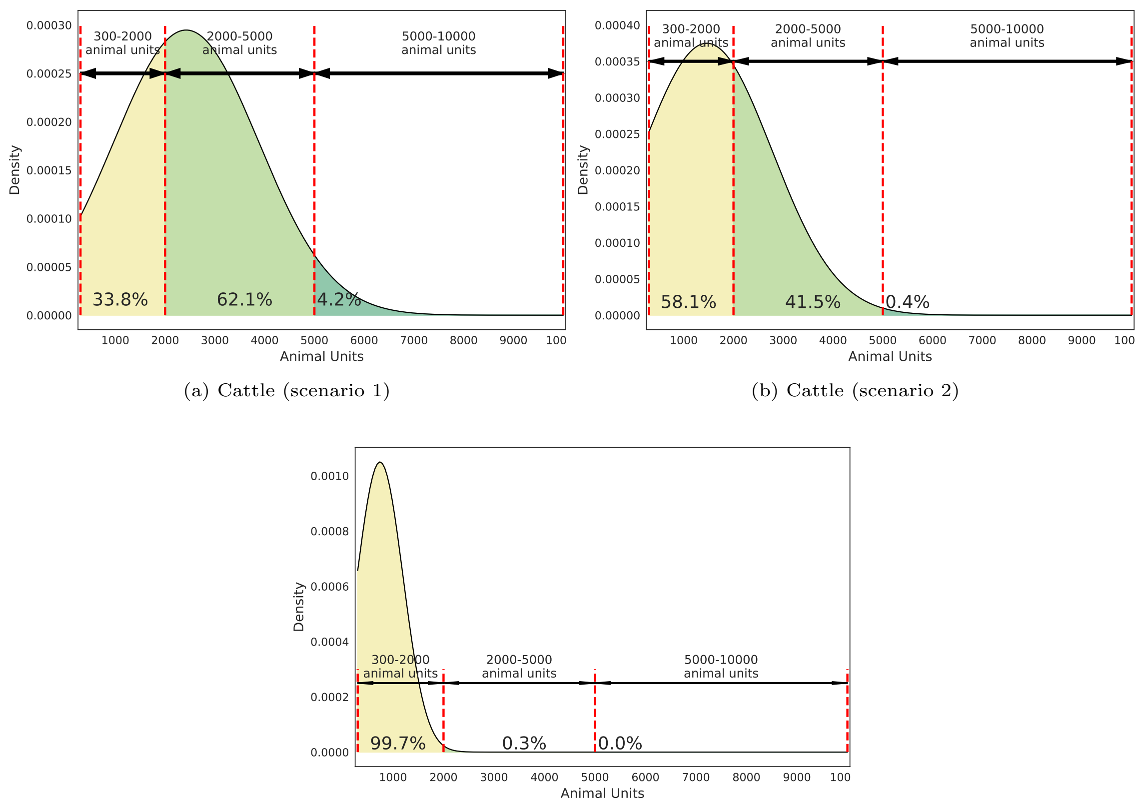
Assessment of different scenarios of P recovery in Ontario, P imports that would be saved, reduction of P dependency of the province, etc (all implications related with mass-balances)

3.2.1. Scenario 1: phosphorus recoverable with current technologies

Agricultural sector. Phosphorus can be recovered from different flows within the agricultural sector, including the production of manure. Phosphorus recovery from cattle and swine manure is performed through struvite precipitation REF REF, existing different processes for struvite production at commercial stage, as described in Section ?REF?. Phosphorus recovery from poulty litter is based on acid extraction and further precipitation (Szögi et al., 2008). Since this technology shows a lower development level, their use has been considered in Scenario 2, see Section ??. Martín-Hernández et al. (2021) determined that the implementation of struvite production processes at livestock facilities is mainly driven by the scale of the CAFO, and thus they can be divided by into three clusters regarding the type of phosphorus recovery processes implemented, i.e., facilities with capacity for between 300 and 2,000 animal units, for between 2,000 and 5,000 animals units, and facilities large than 5,000 animal units. An animal unit (AU) is defined as an animal equivalent of 1,000 pounds (453.6 kg) live weight (U.S. Department of Agriculture, 2011).

The most suitable phosphorus recovery for process for the facilities of each one of these clusters was determined by Martín-Hernández et al. (2021), resulting in that Multiform-type processes are the most suitable struvite produciton system for the cluster including the small-size CAFOs cluster (300-2,000 AUs), NuReSys-type systems are suitable for medium-size CAFOs (2,00-5,000 AUs), while that the suitable struvite system for large-scale CAFOs is Crystalactor-type processes. The investment and operating cost of these systems is collected in Table ?REF?.

The number of cattle animals is reported by the Census of Agriculture at Census Division level REF, but no available data on CAFOs size is available for the province of Ontario. Since this information is essential to determine the suitable phopshorus recovery process to be considered, and in turn the phosphorus recovery cost, the distribution of CAFOs sizes has been approximated to the cattle and swine CAFOs size distribution of other regions in the vicinity of the Great Lakes area, namely Ohio, Pennsylvania, Indiana, Michigan, and Wisconsin. The distribution of CAFOs size in each one of these regions has been approximated through a truncated normal distribution, since the possible size of livestock facilities is bounded between 300 animal units for being considered as an intensive livestock production facility REF, and 10,000 animal units in order to remove extra-large CAFOs that are outliers in the size distribution, avoiding excessive long tails distorting the distributions. For cattle CAFOs, it has been found that two scenarios can be identified, a first scenario (Scenario 1) where the average size of CAFOs is larger, around 2,400 animal units based on the parameters of the states of Ohio, Wisconsin, and Michigan, and a second scenario (Scenario 2) based on the states of Pennsylvania and Indiana where the average size of CAFOs is smaller, lower than 1,500 animal units. Two CAFOs size distributions are proposed for Ontario based on each one of these scenarios, estimating the parameters of Eq. REF as the average parameters of the distributions in each scenario, as shown in 3. For swine CAFOs, the size distribution patterns are similar for all the states studied, with the exception of the Wisconsin, which has been discarded due to the little number of swine facilities installed in this state. A truncated normal distribution with mean equal to 741 AUs and standard deviation equal to 456 AUs is assumed to stimate the distribution of swine CAFOs in Ontario, as shown in 3. The distribution parameters for both cattle and swine CAFOs size are shown in Table 2. The number of CAFOs in each cluster is determined through the Monte Carlo method, with the constrain that the sum of animal units of all CAFOs must not exceed the total number of animal units of Ontario, which for cattle is equal to 1,376,984 animal units for year 2019, which result in the release of 15,923 kt of manure per year and 13.27 kt of phosphorus per year, and for swine represent 506,768 animal units, 5,779 kt of manure per year, and 8.57 kt of phosphorus per year REF. The number of CAFOs belonging to each cluster are shown in Table 2. Further details on the estimation of CAFOs size distribution can be found in the Supplementary Information, Section ??.



(a) Cattle (scenario 1)

(b) Cattle (scenario 2)

(c) Swine

Figure 3: Proposed distribution of CAFOs size in the province of Ontario based on the size distribution of cattle and swine facilities in other regions in the vicinity of the Great Lakes area. Cattle scenario 1 is based on the pattern shown by the US states of Ohio, Wisconsin, and Michigan, which shows an average CAFO size around 2,4000 animal units, while cattle scenario 2 is based on the pattern shown by the US states of Pennsylvania and Indiana, with an average CAFO size around 1,3000 animal units.

3.2.2. Industrial sector

3.2.3. Urban sector

3.3. Economic implications of phosphorus recovery in Ontario

Economic costs or saving derived from the recovery of P in the province and all implications related with economy

3.4. Implications on food sovereignty of phosphorus recovery in Ontario

Implications on food production self-sufficiency derived from the (partial) recycling of P. Discussion on the improvement of the food production system resiliency against disruptions of the global supply supply chains (e.g., current context derived from the COVID-19 pandemia and the war in Ukraine)

3.5. Gaps of knowledge

4. Conclusions

5. Acknowledgments

Pollution Probe

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Table 1: ADD F denotes the phosphorus recovered as $^{\text{kg}}\,\text{P}_{\text{recovered}}/_{\text{year}}$, 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 ??.

Sector	Inflow	Pretreatment	Pretreatment cost (EUR/kg $\text{P}_{\text{recovered}}$)	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 (screw press)	See [1]	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 (screw press)	See [1]	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 (screw press)	See [1]	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 (screw press)	See [1]	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 (screw press)	See [1]	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 (screw press)	See [1]	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 (screw press)	See [1]	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	3	[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)	-	-	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, 60-90% of 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, 60-90% of 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 & food waste	-	-	Chemical extraction and Struvite precipitation	Struvite	94	24.8	3	[8]
		Incineration	6.43	EcoPhos	Phosphoric acid	82	4.5	6	[3,9,10]
		Incineration	6.43	AshDec depollution	Calcium phosphate	86	1.8	6	[3,9,10]
		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]

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)

Table 2: Truncated normal distribution parameters and number of CAFOs in each cluster for the scenarios studied regarding cattle and swine CAFOs size distribution.

Parameter	Cattle (scenario 1)	Cattle (scenario 2)	Swine
mean	2,423.40	1,463.94	741.42
std	1,459.70	1,308.91	455.71
a	300	300	300
b	10,000	10,000	10,000
Number of CAFOs (300-2,000 AU)	177	386	575
Number of CAFOs (2,000-5,000 AU)	324	319	2
Number of CAFOs (>5,000 AU)	22	3	0
Total AUs	13,76,984	13,76,984	506,768