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 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.

2.3.2. Industrial sector

Phosphorus flows through imports, production, exports and waste for the chemical, 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, 2022)

2.3.3. Urban sector

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

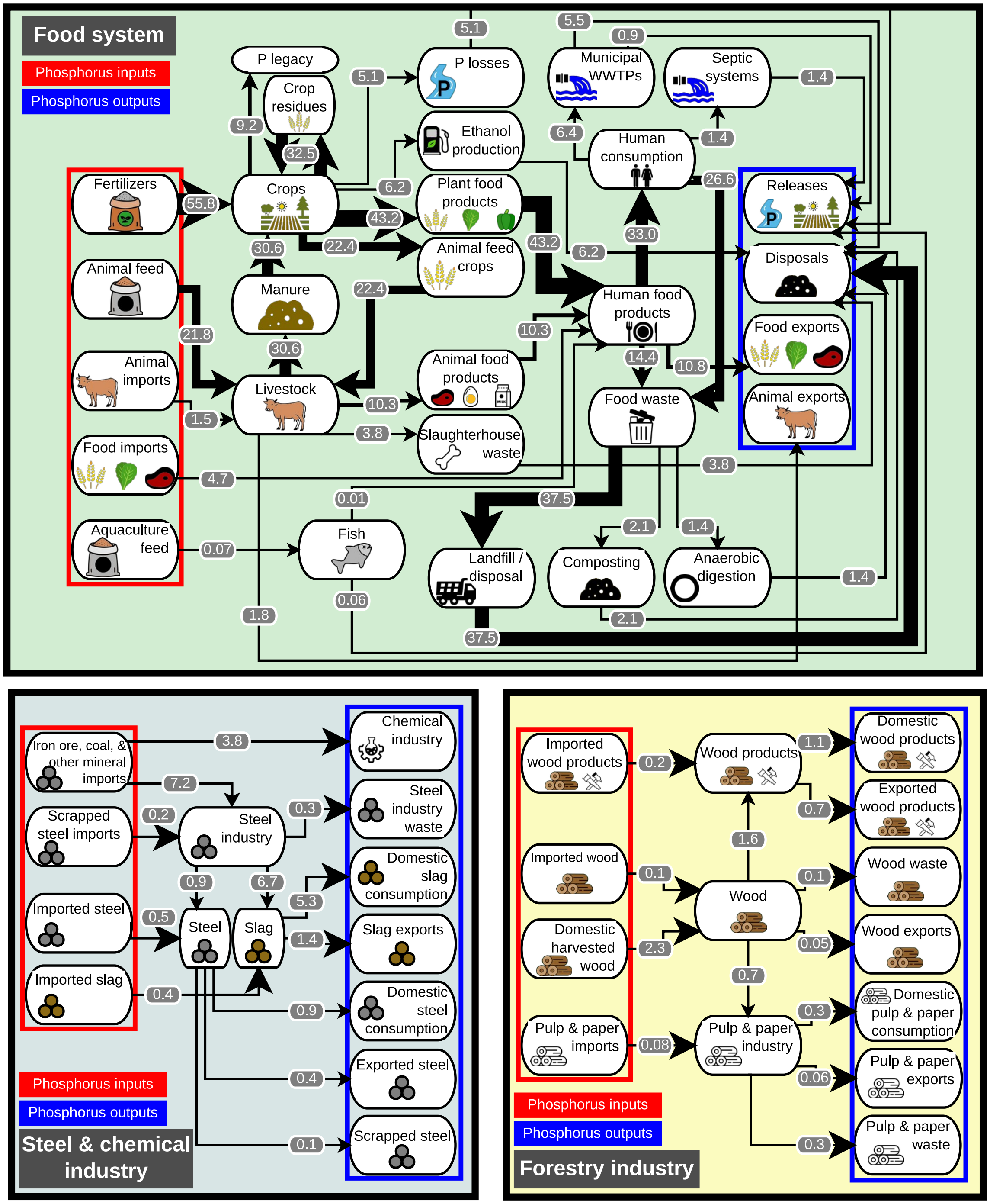

Figure 1: Phosphorus flows in the province of Ontario (kt/year). The streams within red rectangles denote phosphorus inflows into the province, while those streams within blue rectangles denote phosphorus outflows out of the province.

Figure 1 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!

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

Brief overview of potential P recovery techniques for each sector

3.2.1. Agricultural sector

3.2.2. Industrial sector

3.2.3. Urban sector

3.3. 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)

3.4. 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

3.5. 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)

3.6. *Gaps of knowledge*

4. Conclusions

5. Acknowledgments

Pollution Probe

ECCC

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