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Canada: Playing catch-up on phosphorus policy

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Abstract

The concept of sustainable phosphorus is studied in depth around the world, as the scientific community largely agrees that the non-renewable phosphorus reserves in the form of phosphorite ore must be used judiciously. Unfortunately, many developed countries, including Canada, have yet to implement a phosphorus management plan. The Netherlands, Germany, and Switzerland can be heralded as success stories of effective, committed, cross-sector phosphorus management. We examine factors that contributed to their success and consider how these may be transferred to Canada. We also consider Canadian geographic and research factors and contrast the Canadian policy environment and phosphorus recycling efforts with those in the EU. Finally, we analyze active Canadian and North American phosphorus interest groups and seek to determine why their collective efforts have yet to coalesce around tangible action. Canada produces phosphorus fertilizer from imported deposits of phosphate rock. Canada produces potassium fertilizer from its rich potash mines, making it a global power in nutrient production. It is imperative that Canada earns a respected leadership role in efficient global phosphorus and potassium nutrient management and recycling.

Key words: phosphorus recycling, policy, circular economy, food security, phosphorus fertilizer, stakeholder networks, Canada

Introduction

An increasing interest in understanding the major flows, losses, and recycling potential of phosphorus (P) has generated significant bodies of work investigating the global phosphorus cycle (Filippelli 2002, 2008; Cordell and White 2011; Elser and Bennett 2011) and detailed European P-flows (van Dijk et al. 2016). The scientific consensus is that phosphorus must be managed carefully. In 2014, the European Union (EU) added phosphate rock to its list of critical raw materials (European Commission 2014). A range of motivations exist amongst the diverse range of stakeholders in phosphorus acquisition, processing, use, removal from water, and reuse. Those interested in nutrient management are concerned about the consumption rate of phosphate rock, which is the non-renewable, phosphorus-rich, phosphorite ore (Simandl et al. 2011) from which phosphorus fertilizers are produced. Phosphate rock availability, quality, location, and cost all directly affect food security (Dawson and Hilton 2011).

The environmental impetus to manage phosphorus has many motivators: the risk of the eutrophication of waterways with excessive phosphorus inputs that cause algal blooms, the avoidable carbon footprint associated with the transportation and processing of a large fraction of phosphate rock for

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phosphorus fertilizer, and the loss of phosphorus fertilizer along the chain from application to food consumption. Still other groups are primarily interested in improving the human rights of the inhabitants of Western Sahara, where some of the largest remaining phosphate rock reserves are located. Although these groups may have different perspectives on the urgency and priority of implementing phosphorus recycling technologies, all parties agree that the flows of excess phosphorus into waterways and landfills must be reduced.

Modern phosphorus use is not efficient; it is essentially linear, with losses at each stage, from phosphate rock extraction to fertilizer application. Plans for frameworks for phosphorus recovery and reuse are being proposed (Cordell et al. 2011; Kabbe 2013; Egle et al. 2016). At the same time, these phosphorus losses represent an opportunity to recover and recycle phosphorus (**Fig. 1**), contributing to the growing circular economies around the world.

To effectively manage these streams, the regional flows of phosphorus must be understood and matched with economical recycling solutions. In Canada, several groups have studied pockets of this cycle (Ulrich et al. 2009; Metson and Bennett 2015; Metson et al. 2015), but a holistic picture of the Canadian phosphorus cycle has not been assembled and quantified (Trudeau 2014) as it has been for the Netherlands (Smit et al. 2015) and Europe (van Dijk et al. 2016). These many nodes of Canadian activity indicate the presence of the interest and expertise needed to analyze a wider Canadian phosphorus system and identify the conditions to take action. However, for a number of reasons, these projects have yet to crystallize into a concerted, cross-disciplinary Canadian effort. Desmidt et al. (2015) reviewed how different national contexts and drivers explain the range of P-recovery technologies available, although few are operating at scale. The role of national governments through legislation and national policies in enabling phosphorus recycling was also discussed (Desmidt et al. 2015).

To understand how others have generated a sustained national program for phosphorus awareness and directed action, we look to the Netherlands as a case study. We also present a summary of an

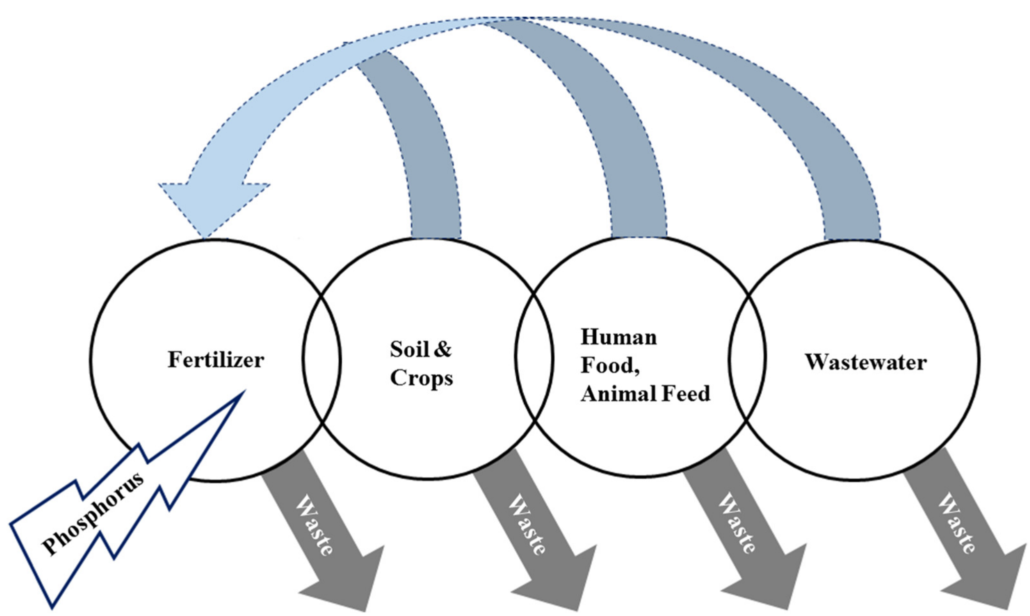

Fig. 1. Options for phosphorus cycles.

EU-funded project based in Germany to contrast the European state of phosphorus affairs with the current Canadian approach to phosphorus management.

Discussion

Dutch success and obstacles, and European progress

The Phosphate Value Chain Agreement was published in October of 2011 (Jansen et al. 2011) by the initial group of 20 companies, universities, government authorities, and NGOs of the Dutch Nutrient Platform (Science Communication Unit (SCU), University of the West of England, Bristol 2013). This group was an early adopter of the concept of the circular economy, or cradle-to-cradle management of resources. Their mandate is to create a "sustainable market … where as many reusable phosphate streams as possible will be returned to the cycle in an environment-friendly way and where the secondary (recycled) phosphate—as long as a surplus exists in the Dutch market—will be exported to the fullest extent possible" by identifying and engaging key players, including the "business community, knowledge institutions and government (the 'Golden Triangle') and NGOs, platforms, and parties" (Jansen et al. 2011, pp. 2 and 10). This consortium thoroughly analyzed economic and environmental considerations of recovering and recycling phosphorus across these sectors. This, in turn, ensured that the various partners with different interests and skills were involved throughout the processing cycle in a streamlined and efficient manner (Smit et al. 2015). Smit et al. (2015) reported an intensive study of phosphorus flows with a three year substance-flow analysis for the Netherlands, which enables data-based decision making about Dutch phosphorus inputs, outputs, and accumulations.

The Netherlands manages a net surplus of phosphorus nutrients, even as they reduce their use of primary phosphorus fertilizers and feed additives. The concept of diverting and processing phosphorus-rich waste into fertilizer and valuable, exportable products is both a practical approach to a waste-management challenge and an opportunity to provide a valuable, recycled resource to their trading partners who import phosphorus (Smit et al. 2015). The Dutch agreement is notable for its specific allocation of long term ambitions, its list of two year goals, and the agreement of many different stakeholders to participate. One outcome of this promotion of phosphorus recycling with struvite precipitation was the improved sludge dewatering observed when precipitation occurred upstream of anaerobic sludge dewatering (Bergmans et al. 2014). This engineering benefit of improved dewatering caused by struvite precipitation reduces the dewatered sludge volume, and hence its transportation and disposal costs.

Coordination and information sharing across a wide range of stakeholders in phosphorus is accomplished in the Netherlands with the Dutch Nutrient Platform (nutrientplatform.org), which inspired the creation of the European Sustainable Phosphorus Platform (ESPP). The ESPP is a thriving communications node, focused on bringing together "companies and stakeholders to address the Phosphorus Challenge and its opportunities" (phosphorusplatform.eu). The ESPP platform serves to nucleate a wide range of stakeholders across the EU, and its content is also available to the global community. Also available online are in-depth reports supported by the EU, such as the 2013 report on Sustainable Phosphorus Use (Science Communication Unit (SCU), University of the West of England, Bristol 2013).

The EU Seventh Framework Programme funded the international research program P-REX from 2012 to 2015 (p-rex.eu). This German-based project demonstrated and validated the phosphorus recovery potential of European processes for phosphorus extraction from wastewater treatment streams and defined strategies for phosphorus recovery from a wide range of municipal wastewater treatment processes and locations. Also within the scope of this project was a recovered phosphorus market potential analysis and "identification of technical, economical, and institutional barriers to the market and provisions of recommendations for market development" (Kabbe 2015a, p. 5). A series of published reports, recommendations, and articles (Kabbe 2015a) were generated by the P-REX project, which also supported presentations and research publications that summarized the current state (at the time) and proposed future phosphorus recovery and recycling possibilities and impediments.

The European Cohesion Policy supports the Interreg NEW (North–West Europe) Cooperation Programme (2014–2020). This transnational cooperation program funds projects across multiple nations, including Phos4You (nweurope.eu/projects/project-search/phos4you-phosphorus-recovery-from-waste-water-for-your-life/). The Phos4You project supports the phosphorus recovery potential of municipal wastewater treatment plants by supporting technology and product development. Deliverables include publishing results on public platforms such as the ESPP and national nutrient platforms, business plan development and technology transfer for circular phosphorus economies, and pursuing the development of policies to legalize phosphorus reuse (NWE Secretariat n.d.). This cross-nation support for a common purpose allows for pooling of economic resources to enable the conditions required to create a circular phosphorus economy.

Comparison of Canada, the Netherlands, Germany, Switzerland, and the European Union

Although progress toward recycling phosphorus in the Netherlands is valuable as a case study to inform Canada's way forward, there are many geographical, cultural, and environmental differences that must be considered. Policy diffusion cannot be applied blindly; it is most effective when there are sufficient similarities between that policy's country and environment of origin and the country interested in adopting it (Cairney 2016). The following is a brief discussion outlining pertinent differences and similarities. Germany is included in this comparison because of its recent progress in recovering phosphorus for reuse and its new regulation for recovering phosphorus from municipal wastewater sludge generated by large wastewater treatment plants (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety 2017), as well as its role in building a wider EU phosphorus network through the P-REX and Phos4You projects. Switzerland is also presented as it recently launched its own online phosphorus network (pxch.ch) and recently passed legislation for phosphorus recovery. Although presently lacking the same cohesive, national, political framework and commitment to a circular phosphorus economy as the Netherlands, the EU is making tangible progress on the creation of a sustainable phosphorus circular economy.

By the numbers

Geography is the most obvious driver of differences between these countries, as summarized in **Table 1** (CIA n.d.). Canada's landmass dwarfs the Netherlands, whose population density is two orders of magnitude greater. The Netherlands has a greater number of people per relative area of water (water density: people/km^2 water) and is more urbanized. These factors may contribute to a generally higher awareness of aquatic issues, and a willingness to direct tax dollars to rectify the visible symptoms that affect a larger fraction of the Dutch population more directly. Although the German and Swiss urbanization and population density per square kilometer are similar, the larger German population and water area generates a higher ratio of people per square kilometer of water (water density). The German water density is almost five times that of the Dutch value, is one and a half times more than the Swiss result, and is over two orders of magnitude higher than the Canadian water density. Although less urbanized than Canada or the Netherlands, Germany and Switzerland have recently passed legislation to increase phosphorus recovery and recycling efforts (ESPP 2017b).

Table 1. Comparative statistics for Canada, Germany, the Netherlands, and Switzerland (CIA n.d.).

Country	Population (No. of people)	Total area (km^2)	Density (ppl/km^2)	Water area (km^2)	Urbanization (%)	Water density (ppl/km^2 water)
Canada	35 362 905	9 984 670	4	891 163	81.8	40
Germany	80 722 792	357 022	226	8350	75.3	9667
Netherlands	17 016 967	41 453	411	7650	90.5	2224
Switzerland	8 236 303	41 277	200	1280	74.1	6435

With its immense footprint, Canada has the lowest density population with respect to both total landmass as well as water area; this also represents a less dense tax base. This dispersion is even more pronounced considering its high rate of urbanization and suggests that Canadian politicians may not rapidly allocate public funds from densely populated cities to solve problems present in remote waterways and farmlands. Because of the municipal wastewater treatment plants operating in many large Canadian urban centres the potential for recycling phosphorus from the human waste stream is simplified due to relatively high rates of urbanization.

The corollary to this, however, is that farms are typically located far from cities, meaning that the phosphorus load in Canadian rural areas is disproportionate to the population. This is further supported when considering the high profile efforts in support of Lake Erie, one of the Great Lakes, that is located in one of the most densely populated areas of Canada, as compared with the attention paid to other Canadian waterways despite significant environmental degradation (Ulrich et al. 2016). Thus, Canada's vast geography will prove to be a significant challenge to improving the political motivation for phosphorus use and recovery.

Phosphorus availability

Two phosphorus availability factors drove the first continental European phosphorus recycling initiative and changed the previous paradigm of phosphorus capture and disposal to avoid eutrophication. The Dutch took action, given the lack of phosphate rock available in the EU (Science Communication Unit (SCU), University of the West of England, Bristol 2013) and their net positive phosphorus flux, largely due to their intense livestock economy (van Dijk et al. 2016).

Despite current surpluses in the Netherlands, the Food and Agriculture Organization of the United Nations (FAO) forecasts a negative phosphorus balance in West and Central Europe over the next three years (FAO 2016). Measured EU 27 Member States (EU-27) imports include mineral fertilizers, animal feed, and food and non-food products, whereas the measured outputs are exports, leaching and manure losses, waste, and agricultural soil accumulation (Schoumans et al. 2015). The phosphorus required by this continent is currently imported (with the exception of Finland), and its value has been noted with its addition to the EU's critical raw materials list. Transformation of local phosphorus waste into a valuable phosphorus commodity generates a source of useful phosphorus products and creates a new economic engine. Schoumans et al. (2015) reviewed the phosphorus balance in Europe and outlined possible solutions by changing the European management of phosphorus, including careful use, recovering, and recycling.

The largest phosphorus waste streams of the EU-27 involve domestic wastewater, which is commonly collected and treated at municipal wastewater treatment plants (Schoumans et al. 2015). Therefore, research teams such as P-REX have focused on reviewing technologies to capture and reuse this waste phosphorus (Hukari et al. 2016). It has been reported that all actors and stakeholders in this change of phosphorus use are required to produce a circular phosphorus economy. Activity at the European, regional, and national levels has established platforms and initiatives at all of these levels (Schoumans et al. 2015).

The phosphorus rock availability in Canada and the US is currently not as dire. In the short term, a modest surplus of phosphorus is forecasted. However, active mines in the US (Potash Corp. 2015) and the planned mines in Canada (Jasinski 2016a) are expected to be depleted within 30 years. This is a luxury not afforded to EU citizens or much of the developing world (UNEP 2011).

However, issues surrounding phosphorus availability and affordability, and food security at large, are also intimately linked to the same factors that contribute to climate change. A significant amount of fossil-fuel energy is required to extract, transport, and process phosphate rock across the world to create the phosphorus fertilizers required to feed the planet (CCME 2012; NZWC 2016). The greenhouse gases associated with nutrient sources that are lost throughout this cycle may be the easiest emissions to reduce, through increased fertilizer application efficiencies and other strategies to increase nutrient use efficiency. Thus, the statement given by Prime Minister Trudeau on the subject of climate change also applies indirectly to food security through nutrient management:

> "*Canada can and will do more to address the global challenge of climate change. We will do so because the science is indisputable, and tells us that our planet is already changing in ways that will have profound impacts on our future. And we will do so because it's the right thing to do, for our environment and our economy, and as part of the global community*".
> Prime Minister Justin Trudeau, 30 November 2015, COP21 (Government of Canada 2015)

This recent political position is an opportunity for Canadian strides to be made in industry, government, and academia to increase fossil fuel energy efficiency as well as agricultural nutrient production and use efficiency.

Regulations

Canada and the Netherland's policies are currently more permissive regarding the use of processed waste as fertilizer than the EU. Dutch legislation approved the use of recovered phosphates such as struvite (an ammonium magnesium phosphate mineral), magnesium phosphate, and dicalcium phosphate as fertilizers from the beginning of 2015. These phosphate products can be recovered from wastewater or agricultural waste and be used if they meet the requirements "for heavy metals and organic micro-pollutants applicable for regular fertilizers" (ESPP 2015). It is possible that the conclusions presented in a report to the Dutch Steering Committee Technology Assessment of the Ministry of Agriculture, Nature and Food Quality (Smit et al. 2009) and the research into the safety of struvite as a recovered fertilizer from wastewater (Gell et al. 2011) contributed to a data-driven Dutch policy decision.

The EU has not yet amended their legislation to allow for the same, effective re-use of recovered phosphates, as recycled products must meet end-of-waste criteria (European Commission 2016). A forward-looking German publication on sewage sludge management summarizes current approaches to sludge management, the legal and regulatory frameworks associated with sludge reuse, and includes a chapter on phosphorus recovery (Wiechmann et al. 2013). Introducing the anticipated phosphorus peak in 2033 (Cordell et al. 2009), and noting the limited phytoavailability of phosphate as iron phosphate (Römer and Samie 2001), which is a common product in sludge, the report outlines the work required to extract useful phosphorus from sewage sludge to meet demand while complying with regulations.

German use of sewage sludge for fertilizer must meet the Biological Waste Regulation (BioABfV), the Sewage Sludge Regulation (AbfKlär), and the limits set by the Fertilizer Ordinance of Germany

(DüMV); European funding supports research projects to evaluate phosphate recyclate and conventional phosphorus fertilizer toxicity (Rastetter et al. 2017). EU-funded projects such as P-REX supported the undertaking of a quantitative risk assessment of PRs for environmental and human health impacts (Kraus and Seis 2015). These data are imperative to crafting future European policy to protect the environment, human health, and enable phosphorus recycling from sewage sludge. Also important for steering society toward taking action are funding publications that clearly report data and recommend action (Kabbe 2013).

An analysis of the EU legislation that regulates phosphorus recovery was recently conducted, reporting on the "production, trading and use of recovered and recycled phosphorus", in particular as a fertilizer from wastewaters (Hukari et al. 2016, p. 1128). In place are protection laws for health and the environment, as well as fertilizer market regulations. National solutions are often needed to facilitate the permit process for recycling phosphorus products (Hukari et al. 2016). Related laws for Czech Republic, Germany, Spain, and Switzerland were summarized as part of the P-REX project (Nättorp et al. 2014). Across the EU, "fragmented decision-making in regional administrations" applies to phosphorus recycling (Hukari et al. 2016, p. 1127), although the EU Waste Framework Directive has generated legislative terminology for phosphorus recovery (European Parliament 2008).

The current European legislation that governs phosphorus recovery technologies and their products focuses on both "recovery and recycling installations and processes" or "market placement of the recycled materials", with the goal of protecting the environment and human health (Hukari et al. 2016, p. 1130). It is possible to construct phosphorus recovery facilities and place a recovered phosphorus product on the market, but there is room to improve the legislation that could facilitate the acceptance of new phosphorus recovery and reuse technologies. Hukari et al. (2016) noted that challenges that impede new phosphorus-recovered products include slow and expensive administrative legal processing, regional evaluation of the end-of-waste status, and EU acknowledgement of new products. The end-of-waste criteria "specify when certain waste ceases to be waste and obtains a status of a product (or a secondary raw material)" (European Commission 2016). Hukari et al. (2016, p. 1133) concluded that EU legislation "neither hinders nor actively supports building of recovery installations and market entry" of phosphorus, and noted that phosphorus recovery and recycling actors are a heterogeneous group that may be challenging to regulate effectively.

Despite these complexities, the German government recently approved the obligatory recovery of phosphorus from wastewater treatment plants larger than 50 000 person equivalents (p.e.). Phosphorus recovery from these plants will be required "… if the sludge contains more than 2% phosphorus/DS (dry solids) or have to incinerate the sludge in monoincinerators" (ESPP 2018). In 2015, approximately 25% of German municipal sludge was regulated for use in landscaping and as agricultural fertilizer, with the balance sent to landfill or used as fuel in power or cement plants. Landfilling of this waste was permitted after pre-treatment by incineration or after mechanical-biological treatment. This Ordinance on the Reform of Sewage Sludge Utilisation was legislated in October 2017. It is an amendment of the 1992 Sewage Sludge Ordinance "in order to return the valuable constituents of sewage sludge (phosphorus) to the economic cycle more intensively … and at the same time, to restrict conventional soil-related sewage sludge utilisation with a view to further reducing pollutant inputs into the soil" (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety 2017).

The Federal Office for the Environment (FOEN) of the Swiss government published a study of their phosphorus flows (FOEN 2009). This study "represents an essential step enabling the potential for increasing material efficiency and reducing risks of the phosphorus cycle to be adequately assessed from a holistic standpoint" (FOEN 2009, p. 16). This work allowed for the understanding that Switzerland is a net importer of phosphorus and that their phosphorus cycle is dominated by agricultural (feed and manure) and disposal activities. Proposals for future action were made to "illustrate the substantial potential for closing the phosphorus cycle in Switzerland" (FOEN 2009, p. 18). The Swiss government engaged closely with municipal governments, industry, and environmental groups to develop a coherent strategy (DETEC 2015). A Swiss regulation successfully took effect as of 1 January 2016 that will lead to "obligatory technical recovery and recycling in the form of inorganic products from all sewage sludge and slaughterhouse waste" within 10 years (Conseil fédéral suisse 2015; ESPP 2016, p. 13). One of the key considerations in the implementation of recovery technology is ensuring that soil quality is protected, specifically with respect to "heavy metals, organic contaminants and pathogens and criteria for phosphorus solubility" that may be transferred to the soil (ESPP 2017a, p. 2). The approach taken in this Mineral Recycled Fertilisers regulation is less prescriptive than the proposed EU Fertiliser Regulation, which "specif(ies) input materials and process parameters as well as quality and safety criteria for the final product" (ESPP 2017a, p. 2). The Swiss government is continuing to consult with the public and stakeholders to ensure that realistic targets and timelines are established (ESPP 2017a).

The Canadian Council of Canadian Ministers of the Environment (CCME) conducted a review in 2010 to study the regulations surrounding recycle nutrients from human waste; one of the explicitly stated concerns in this report was the long-term supply of phosphorus (CCME 2010). A follow-up report was produced in 2012 that clarified how and where processed human waste can be reused (CCME 2012), including links to the pertinent Canadian Food Inspection Agency (CFIA) requirements. This report went so far as to recognize that removing phosphorus from wastewater in a way that allowed beneficial reuse was preferable to methods that would lead to disposal of phosphorus end products. Although this puts Canada in the enviable position of generating policy to allow and encourage nutrient recycling, it is not yet a reality, possibly due to the economic costs and risks associated with new technologies. The current costs of phosphorus recycling technology mean that the resulting recycled phosphorus product is not competitive on the market (Oleszkiewicz 2015). Canada also lacks the forward-looking Dutch Phosphate Value Chain Agreement, the commitment of the wide range of Dutch stakeholders who are part of the Agreement, and the commitment to fund a holistic research project to understand that potential and impediments for phosphorus recycling.

Policy networks

The Dutch recently developed and approved the policy to permit the reuse of recycled phosphorus fertilizers. This enables the members of their Phosphate Value Chain Agreement to further develop and profit from their collaborations and inventions. Policy networks are described as "the relationships between actors responsible for policy decisions and the 'pressure participants' such as interest groups, or other types or levels of government, with which they consult and negotiate" (Cairney 2016, p. 28). This depiction describes the many different players involved in the Netherlands, and also in the EU, across industry, academia, government, and other interest groups. A key ingredient in the Dutch success could be their Nutrient Platform for actively sharing successes and setbacks in a manner that enables individuals and organizations to learn from each other; the EU has implemented its own platform for sharing this information between countries (Nutrient Platform NL n.d.). The ESPP has proven to be a key facilitator in connecting these various groups across Europe and in providing a stable communication network to strengthen connections, enable productive collaborations, and share information.

Despite significant progress toward capturing and recycling phosphorus at different stages of the phosphate value chain around the world, the EU's legal framework surrounding nutrient recovery has been described as limiting "due to legal barriers for the integration of waste material" (Kabbe 2015b). This means that even when phosphorus has been recovered in a form that meets the requirements for an absence of pathogen and contamination levels the sale of such a recycled product is not permitted. However, this impediment has motivated a revision of the EU's fertilizer regulation as one of the initiatives within the circular economy package that is currently underway (European Commission 2015). There is no European policy to affect phosphorus legislation, although some European Community Member States have limitations on the application of phosphorus (Amery and Schoumans 2014, cited by Schoumans et al. 2015).

The Canadian counterparts of these organizations have yet to organize and share resources around this complex issue of nutrient flow quantification, use efficiency, and recycling. The nodes existing across Canada typically cluster around the subject of avoidance of eutrophication by academic institutions, some government organization, or around a specific body of water, but they lack a central point of cohesion. Just as Canada's size may seem to contribute to increasing the distance between the phosphorus problem and the average citizen, it also makes it more difficult for scientists and policymakers to be up to date on Canadian activities and advances with respect to phosphorus use. Identifying these groups and simplifying information transfer may assist in recognizing trends or possible candidates to galvanize a larger, coordinated Canadian effort.

Analysis of Canadian phosphorus players

This section focuses on various players involved in phosphorus cycling within Canada. It seeks to both categorize the stage of the cycle that is of most interest, as well as understand the underlying motivation. The players and corresponding phosphorus value stage(s) are presented in **Fig. 2**.

Industry

Within Canadian industry there are relatively few actors involved in phosphorus processing. Raw phosphate rock extraction and (or) processing into phosphorus fertilizer is an industry valued at $36 billion CAD; the 2017 merger of Agrium Inc. and Potash Corp. into Nutrien™ resulted in the world's largest producer of potash, and the second largest producer of nitrogen-based fertilizer, that also produces phosphorus fertilizer (CBC 2016; Jamasmie 2017). Phosphorus processing is relatively expensive compared with potash and nitrogen, and, as such, it contributes approximately 11% to each of the overall profit margin of both companies (Agrium 2015; Potash Corp. 2015).

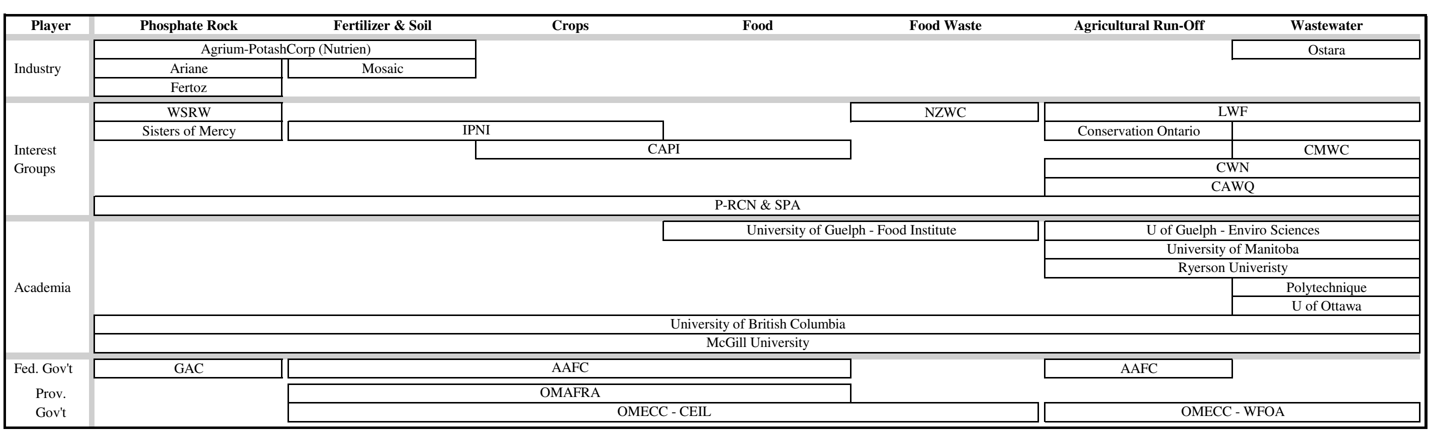

Fig. 2. Canadian players throughout the phosphorus cycle. AAFC, Agriculture and Agri-Food Canada; CAPI, Canadian Agri-Food Policy Institute; CAWQ, Canadian Association of Water Quality; CEIL, Circular Economy Innovation Laboratory; CMWC, Canadian Municipal Water Consortium; CWN, Canadian Water Network; ECCC, Environment and Climate Change Canada; GAC, Global Affairs Canada; LWF, Lake Winnipeg Foundation; NZWC, National Zero Water Council; OMAFRA, Ontario Ministry of Agriculture, Food, and Rural Affairs; OMECC, Ontario Ministry of Environment and Climate Change; P-RCN, Phosphorus Research Coordination Network; SPA, Sustainable Phosphorus Alliance; WFOA, Waste Free Ontario Act.

An interim report on Canadian sedimentary phosphate deposits from 1978 noted that "Canada has a well-developed phosphate industry although no ore is mined in this country" (Christie 1978, p. 1). A 2010 report by the International Fertilizer Development Centre (IFDC) listed the only Canadian phosphate rock reserves of the Kapuskasing mine operated by Agrium and the resource data for the Martison Project by Phoscan (Van Kauwenbergh 2010). A 2016 United States Geological Survey (USGS) report stated that "no phosphate rock was produced in Canada in 2014 and 2015" (Jasinski 2016b, p. 125); this is due to the 2013 Kapuskasing mine closure (Rodya 2012). There are no currently active phosphate mines in Canada, although three phosphorus mines are being developed: Lac à Paul (Arianne), Wapiti (Fertoz), and Martison (Phoscan). The 2017 Map of Top 100 Exploration Projects in Canada did not include a phosphate deposit (Natural Resources Canada 2017). Considering that Canada has 0.1% of the world's phosphorus reserve, the output of potential mines is negligible on a global scale (USGS 2015, 2016).

The only business currently selling phosphorus recovery technology from municipal wastewater treatment plants in Canada is Ostara, which is a Canadian company founded at the University of British Columbia (National Research Council 2012). Ostara's Pearl® process currently produces struvite in Saskatoon and Edmonton; in contrast, eight processes are operating in the United States and three are operating in Europe. The Ostara process produces an ammonium-magnesium-phosphate mineral called struvite that is recycled from municipal wastewater treatment plants, meets the fertilizer specifications of the Canadian Food Inspection Agency (CFIA), and is marketed as Crystal Green®. However, it is not widely available in Canada. It is used as a special additive in other fertilizers and is marketed for golf courses (Crystal Green® n.d.). The barrier for this recycled phosphorus fertilizer product to enter the Canadian market, thus, seems to be availability rather than regulations prohibiting its use, as is the case in the EU. A 2012 report from the Council of Canadian Ministers of the Environment (CCME) acknowledged that there are many benefits to applying recycled nutrients to the soil as long as they met hygienic standards required of fertilizers by the CFIA (CCME 2012).

Interest groups

A range of Canadian groups have different interests in phosphorus. From its source as phosphate rock, to phosphorus use in fertilizer for crops and food, as a waste product, and the integration of a complete phosphorus cycles, Canada hosts many active communities with an interest in phosphorus.

Phosphate rock

There are two Canadian interest groups that have repeatedly voiced concerns over the human rights situation in Western Sahara, which holds extensive phosphate rock reserves. The Sisters of Mercy are shareholders in Potash Corp., and in a 2015 shareholder meeting they submitted a resolution requesting that a review be conducted to ensure that Western Saharans who live near the phosphate rock deposits were being well treated. They submitted a similar request to Agrium Inc. Although both companies acknowledged these concerns, neither initiated an external review (Allen 2015).

The second, more aggressive interest group is known as the Western Sahara Resource Watch (WSRW). Their mission is to inform commodity traders of the situation in Western Sahara and encourage them to halt phosphate rock procurement until a solution has been reached to enable the local Saharawi people to exercise their right to self-determination. Their efforts in petitioning countries that purchase phosphate rock from Morocco have led to several countries, including Norway, Germany, and Australia (WSRW 2016), to acquire phosphate rock elsewhere.

Fertilizer, crops, and food

The International Plant Nutrition Institute (IPNI) is a global organization, but its phosphorus project is headquartered in Guelph, Ontario. IPNI is most focused on fertilizer use for crop growth.

IPNI promotes the 4R program (Right source, Right rate, Right time, Right place) (Schröder et al. 2011; IPNI 2012) to reduce fertilizer waste and run-off to the hydrosphere. Although IPNI acknowledges that a sector of the scientific community is concerned about the depletion of global phosphorus, it is less concerned with this long-term view, and instead chooses to focus on improving current farming practices (Bruulsema 2016).

The Canadian Agri-Food Policy Institute (CAPI) is a think tank that analyzes the various policies affecting the agriculture industry, recognizing that the system is complex. They seek to bring players in the food supply chain together with researcher and government representatives from across all Canadian provinces (Skogstad 2011). Although they are concerned about the impact of climate change on crops and food production, the scope of their interest does not include phosphate rock or phosphorus in wastewater (CAPI 2016).

The National Zero Waste Council (NZWC) was founded in Vancouver in 2013 and now includes groups in Toronto, Montreal, Halifax, and Edmonton. Their interest lies in preventing the avoidable waste of food and other goods by collaborating with government and businesses to enable reuse or recycling of goods, and to prevent superfluous waste production (NZWC 2016). They submitted recommendations to the Canadian government regarding strategies for reducing food waste, with the consequent reduction in carbon emissions (NZWC 2016).

Waste

The Canadian Water Network (CWN) and the Canadian Municipal Water Consortium (CMWC) are both active on the subject of phosphorus. Notably, in 2015 they commissioned a report from the University of Manitoba, Options for Improved Nutrient Removal and Recovery from Municipal Wastewater in the Canadian Context (Oleszkiewicz 2015). This detailed report provides background not just on Canadian considerations, but also compares different and related regulations across the world. One of the greatest strengths of these two networks is that they are active across the country, which is a challenge not easily overcome due to vast distance and multiple time zones.

The complete cycle

There are two North American groups whose mandates span the entire phosphorus cycle, both of which are based in Arizona State University (ASU). The Phosphorus Research Coordination Network (P-RCN) was formed in 2013 and takes a multidisciplinary approach to academic research as well as engaging policymakers. Recognizing that industry players should also be included, the P-RCN activated another group. Inspired by the success of the ESPP, the North American Sustainable Phosphorus Platform (NASPP) was announced in the January 2014 ESPP newsletter (ESPP 2014). Since that time, the name has changed to become the Sustainable Phosphorus Alliance (SPA), although the purpose of the group continues to focus on bridging the gap between academic and industrial teams with an interest in phosphorus. The SPA recently participated in a North American event with a range of phosphorus stakeholders to develop a series of transition pathways to improve phosphorus sustainability (Jacobs et al. 2017). Neither of these groups is as active as the ESPP; thus, there is still a gap in the North American phosphorus network. Given the utility and success of the ESPP across a wide range of stakeholders, there is an opportunity to bring together Canadian academic, government, and industrial parties, and take advantage of existing clusters of activity across the country to form a Canadian phosphorus policy platform.

Academia

Participation by various Canadian universities spans the entire phosphorus cycle. There are several regional hubs where there is significant activity. The University of British Columbia, where the Ostara struvite production process was developed (Britton et al. 2005), is also a partner with the

Australian phosphorus network (Phosphorus Futures n.d.). The University of Manitoba was involved in producing a report commissioned by the Canadian Water Network (Oleszkiewicz 2015); it has also studied phosphorus through the lens of subject of phosphorus impact on Lake Winnipeg (Ulrich et al. 2009, 2016). Scientists at the University of Manitoba also compared water quality data with phosphorus risk indicators (Salvano et al. 2009). The University of Guelph is home to the Arrell Food Institute whose vision is to transform global food systems. Further, the Department of Land Resource Science has been active in Africa for over 20 years, studying use of phosphate rock for agriculture (van Straaten 2002).

An international collaboration that included the University of Saskatchewan and Trent University reported phosphorus fluxes in the Beaver River (Ontario) (Baulch et al. 2013). The Urban Water Lab at Ryerson University hosted a conference in 2014, Phosphorus as a Resource: Sustainable Solutions for Infrastructure, Food Security and the Environment (Trudeau 2014). Ryerson University was also commissioned by the Canadian Water Network to prepare the 2015 report, Risks Associated with Application of Municipal Biosolids to Agricultural Lands (McCarthy 2015). McGill University is home to researchers who have published extensively on phosphorus recycling efforts in the US and in Montreal and have collaborated on articles with members of the EU phosphorus network. The McGill Geography Department also has a very pertinent international project to define the concept of a nitrogen footprint. In Quebec, Université Laval's Applied Biological Sciences Department has extensively studied nutrient recovery (Vaneeckhaute et al. 2013, 2017). École Polytechnique (Montreal) Civil Engineering Department's research on phosphorus capture using apatite (a calcium phosphate mineral) has the potential to be part of a phosphorus recycling strategy (Bellier et al. 2006). Successful phosphorus data collection efforts at Laval are also important to quantify the trophic status of lakes in Quebec (Galvez-Cloutier and Sanchez 2007).

Examination of the author lists from publications arising from these research groups suggest that they are mostly working in isolation. Canadian researchers have published with and partnered with scientists from the US and EU more than with each other. Although these foreign collaborations advance their own research programs they do not foster the development of knowledge and awareness of pan-Canadian phosphorus cycles.

One example of academic (Université Laval, University of Guelph, McGill University) and governmental collaboration (Agricultre and Agri-Foods Canada) is the development of a predictive tool for phosphorus movement from agricultural land to water in the Canadian Great Lakes basin (Allaire et al. 2011). There has been productive Canadian collaborative research that focuses on the study of phosphorus flows from agricultural land to water, with the goal of understanding these fluxes and relating this to eutrophication events.

Government

The mandates of several departments have led to participation in various aspects of phosphorus cycling, as summarized in **Fig. 2**. Although there seems to be collaboration between federal and provincial counterparts (i.e., CCME), there are few cases of departments working together where their mandates overlap. One exception was a collaboration between Agriculture and Agri-Food Canada (AAFC) and Environment and Climate Change Canada (ECCC) who together reported on a study that developed environmental thresholds for phosphorus and nitrogen in streams, as part of a National Agri-Environmental Standards Initiative to protect agricultural streams (Chambers et al. 2012), and demonstrated the value of long-term databases. AAFC generated an indicator of risk of water contamination for phosphorus (IROWC-P) (Bolinder et al. 2000) and has measured trends in Quebec (van Bochove et al. 2007) and Canada (van Bochove et al. 2006, 2012). It is not clear if this information is being used to motivate Canadian phosphorus recycling policy. AAFC has collaborated on an international level on the subject of phosphorus excess in soils and agricultural management (Sims et al. 2000). To make any meaningful changes beyond agricultural practices, their respective efforts will need to complement and reinforce each other.

Federally, ECCC has the highest profile phosphorus-specific project, and is collaborating with the United States Environmental Protection Agency (USEPA) to improve the water quality of Lake Erie. Lake Erie is a geographical location where regulatory effort is currently focused and potential instruments are being studied. AAFC is also cognizant of phosphorus use issues related to farming. Although it is tracking phosphorus concentrations and their associated risks, it is only imposing voluntary corrective measures (AAFC 2016a), with the intention that cost savings associated with reducing waste would be sufficient financial incentive. AAFC is also sponsoring a project and has published several papers related to responsible phosphorus use; however, these are focused more on good farming practice and plant uptake than on the larger phosphorus cycle (AAFC 2016b). Thus, ECCC currently has the greater Canadian role in implementing regulations and incentives, although these are focused primarily on keeping phosphorus out of waterways, without considering phosphorus' value as a resource to be recycled.

There is no evidence that Global Affairs Canada (GAC) is specifically tracking issues surrounding phosphorus or phosphate rock in Western Sahara. However, due to the large economic activity and significant Canadian companies in this industry it would be naïve to assume that they are not monitoring the situation. Agrium Inc. has an agreement with the Moroccan *Office Cherifien des Phosphates (OCP)* to supply phosphate rock until 2020 (Agrium 2015), though this agreement is not specifically mentioned in GAC's Morocco Factsheet (GAC 2015).

On a provincial level, both the Ontario Ministry of Agriculture, Food, and Rural Affairs (OMAFRA) and the Ontario Ministry of the Environment and Climate Change (OMECC) have participated in phosphorus sustainability conferences (Trudeau 2014) and collaborative publications (Joosse and Baker 2011). The primary phosphorus focus of OMECC involves the ecosystem of the Great Lakes (Wynne 2016), which, again, is largely Lake-Erie-centric. However, after the Waste Free Ontario Act received Royal Assent in June 2016 (Legislative Assembly of Ontario 2016), the situation has changed, leading to opportunity to harness Ontario's entire phosphorus cycle. For instance, OMECC recently launched the Ontario Circular Economy Innovation Lab (CEIL) with the goal of bringing together public and private sector representatives to collaborate in developing innovative ways to reduce waste and lower greenhouse gas emissions (Circular Economy Innovation Lab n.d.). These developments could contribute to connecting the many active phosphorus players in Ontario. A recent publication from a joint meeting between the Ontario Geological Survey, the Geological Survey of Canada, and Conservation Ontario included a presentation that outlined the actions needed in the agricultural sector to reduce phosphorus flows to Lake Erie (Cushman et al. 2017).

A report prepared for the Water Quality Task Group of the Canadian Council of Ministers of the Environment was an effort "to investigate the feasibility of developing ecoregion-based phosphorus guidelines in Canada by using Ontario as a case study" (Gartner Lee Ltd. 2006, p. 2). This report was one of the outcomes of the Canadian Guidance Framework for the Management of Phosphorus in Freshwater Systems to discuss the potential of creating ecoregion-based phosphorus guidelines because of the wide differences in Canadian geology, climate, soil, and vegetation, which influence water quality (Environment Canada 2004a, 2004b). Although this work is a promising focus of efforts, there is no obvious Canadian leader to synthesize Canadian phosphorus activities, nor are the solutions to phosphorus problems simple or even apparent. Disparate interest groups are all in agreement that phosphorus must be used judiciously. The challenge in effecting Canadian change toward managing phosphorus has been to identify a common purpose and project a united front.

Ulrich et al. (2016, p. 1037) made an interesting observation regarding the role of government versus non-government sectors in the case of action in the Lake Winnipeg basin, noting that “the impetus for change seems to be much stronger in the non-government sectors”. It may be that part of the government’s apprehension is due to the scope of the problem; the far-reaching phosphorus flows do not fit easily into one governmental department’s mandate. This means that it would take significant coordination and weighing of various interests, and any activity may therefore remain well outside any given mandate. Thus, a successful Canadian platform may need to be formed as a body separate from any one particular government department, though still aligned with and supported by them.

It is salient at this juncture to discuss a workshop, Phosphorus as a Resource: Sustainable Solutions for Infrastructure, Food Security and the Environment, that took place at Ryerson University in 2014. Many of the interest groups, academic institutions, and governmental departments mentioned above were represented, as well as members of the ESPP. A summary of these discussions was collected and published in the proceedings, and of particular interest was the Initial Action Plan for Engagement (Trudeau 2014). The areas listed as requiring action are worth repeating here, as they are still pertinent:

1. Lack of knowledge of the need to recognize phosphorus as a resource;
2. Lack of coordination for governance, technology and research focused on recycling;
3. Requirement for support of market instruments; and
4. Recovery/reuse linkage to a broader nutrient–energy–water nexus.

This workshop was the genesis of two valuable reports on nutrient recycling commissioned by the CWN (McCarthy 2015; Oleszkiewicz 2015). However, without the implementation of a central coordinating authority or viable information management infrastructure to share knowledge, the effort may stagnate. For phosphorus recycling to regain momentum, a stable platform for Canadian stakeholder engagement and information exchange must be created to provide a source of information and a mechanism to collaborate and coordinate action across a wide range of stakeholders.

A similar event to the 2014 Workshop was held in Toronto on 8 March 2018. Sponsored by the Everglades Foundation, the International Institute for Sustainable Development (IISD), MOECC, and ECCC hosted a National Nutrient Reuse and Recovery Forum, which invited speakers to present information on various aspects of the phosphorus problem. Although many important updates were presented and discussed, it will take significant effort and coordination to ensure that the discussion held at the Forum will have greater lasting power than previous events and spur key stakeholders into action.

The act of uniting toward a common purpose is a powerful driver for bringing a community together. Because the efforts required to mobilize a phosphorus community span a range of communities, purposes, skills, and interests in different sectors of the phosphorus cycle, and there is no impending phosphorus surplus or deficit, Canada has not yet had that lightning rod opportunity or event to crystallize the intentions of the many interested parties. The phosphorus problem simply is not perceived to be particularly urgent, outside of a few small interest groups. Furthermore, the responsibility to resolve the issues of phosphorus loss to the environment, phosphorus capture, and phosphorus recovery is spread across the country as well as within governments.

There remains little debate amongst stakeholders that phosphorus is a limited resource, agriculture is an important factor in the Canadian economy, and Canadian phosphorus recycling technology from wastewater exists. However, even given this information, recycling phosphorus from municipal wastewater is not common in Canada. The work of a Canadian platform must, thus, be in further increasing awareness, studying both the financial and regulatory incentives, and bringing together stakeholders across the phosphorus cycle to ensure that all interests are addressed.

Conclusion

Harnessing and optimizing Canada's phosphorus cycle is a complex problem that must be tackled on many different fronts. Due to Canadian challenges of geography, population density, politics, and industrial and economic drivers, there is no urgent national motivation to generate a phosphorus recovery and recycling program. To date, the only symptom of a systemic, Canadian problem with the phosphorus cycle that is being addressed is to understand phosphorus flows as they relate to eutrophication. As such, targeting this obvious and understandable problem, and its relationship with agriculture, may be the easiest foot in the door to drive improvements in the efficient use of phosphorus throughout the entire cycle.

There are hubs of activity around certain academic institutions, and within government; the federal ECCC currently has the greatest relevant expertise, although ECCC's focus is not on the circular economy opportunity that this problem presents. There are many other groups whose interests overlap, yet they have not been actively engaged to participate in a discussion of the larger Canadian phosphorus cycle. To effect real change in Canada, industry, academia, and other stakeholders must acknowledge their common purpose, and perhaps consider the Dutch approach, while learning from the technical and legislative progress made in the EU. Understanding phosphorus flows, bringing a wide range of stakeholders to the table, and a communal commitment to short and long term objectives are goals that could result in a holistic network to advance Canadian shared and diverse interests in phosphorus recycling.

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Author contributions

JZR conceived and designed the study. JZR and SO performed the experiments/collected the data. JZR and SO analyzed and interpreted the data. JZR and SO contributed resources. JZR and SO drafted or revised the manuscript.

Competing interests

The authors have declared that no competing interests exist.

Data accessibility statement

All relevant data are within the paper.

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