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Dynamic simulation of phosphorus flows through Montreal's food and waste systems

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ABSTRACT

Phosphorus (P) is an important nutrient, essential to plant growth and agricultural production, however it can also act as an aquatic pollutant. Anthropogenic activities have impacted global P flows—causing increased mobilization of P to waterways and accumulation of P in landfills. Cities play a unique role in P management because they tend to concentrate demand for P-rich products and subsequent waste production. After developing a substance flow analysis of current P flows in Montreal, we use a system dynamics model to explore the flows of P on the island from 2008 to 2050 under four scenarios. The scenarios are based on existing trends, impending policies, and possible social change. We found that presently over 80% of P imported onto the island ends up in landfill, another 17% flows to the Saint Lawrence River, and less than 3% is available for recycling. There is significant potential to recover P from both wastewater and solid organic waste on the island of Montreal, and to reduce P flows to landfill by up to 95%. Given that existing policies in Montreal support organic waste diversion and wastewater treatment, information gained through our study can be utilized to make P policy and management decisions that fit readily into these current policies. This study shows leverage points where Montreal has the most potential to improve its P management, reducing the use of synthetic fertilizers and reducing P pollution. Furthermore, this model can be used to guide future research analyzing P flows in urban settings.

1. Introduction

Phosphorus (P) is an essential plant nutrient and is required in agriculture to produce food for a growing global population (Klinglmair et al., 2015). P is considered to be a finite resource and has no substitutes (Theobald et al., 2016). On the other hand, P can often act as a powerful aquatic pollutant (Carpenter et al., 1998). This leads to a two-sided challenge in which P is both a scarce resource and, at the same time, a threat to aquatic ecosystem health (Elser and Bennett, 2011).

Anthropogenic activities, such as industrial agriculture and the treatment of waste products, have dramatically altered the P cycle on both global and regional scales (Bennett and Schipanski, 2013; Childers et al., 2011). Over 220 million tonnes of phosphate rock are mined annually from geographically concentrated rock deposits (Jasinski, 2016). Approximately 90% of this P is used in agriculture (Brunner, 2010; Cooper et al., 2011). The mobilization of P from mineral deposits through anthropogenic food and waste systems has dramatically accelerated the global P cycle (Carpenter and Bennett, 2011; Villalba et al., 2008). Within the current P cycle, there are dissipative losses of P to waterways from agriculture through inefficient use of fertilizer (when applied in excess of plant demand) and from wastewater effluent, as well as further losses when organic waste and biosolids, rich in P, accumulate in landfills (Klinglmair et al., 2015; Nilsson, 1995; Theobald et al., 2016). These losses reinforce issues related to both P scarcity and pollution as it is used in surplus of plant requirements and accumulates in waterways. This linear, accelerated flow of P, from extraction to consumption with limited recycling, far exceeds the geological timescale at which phosphate rock is replaced, making the current management of P unsustainable (Hamilton et al., 2015).

Urban systems can play an important role in regional and global P flows. Many existing studies that map regional P patterns note the development of P "hot spots" in urban areas, where the demand of P-rich organic products (e.g. food) and the subsequent P-rich waste is concentrated (e.g. Cooper and Carliell-Marquet, 2013; Egle et al., 2014; Klinglmair et al., 2015; Metson and Bennett, 2015b; Neset, 2005; Senthilkumar et al., 2014). As more of the world's population migrates

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to urban areas, these cities play an ever-increasing role in both global and regional P cycles and our ability to recycle and reuse P (Kennedy et al., 2007).

Substance flow analyses (SFA) of P in urban areas help quantify the amount of P moving through these regions and identify important stocks and flows of P in urban systems. Typically, the goal of a P SFA is to better understand P flows in order to inform policies that acknowledge and address the challenges of P by reducing the use of non-renewable reserves while limiting unwanted flows of P to waterways (Neset, 2005; Chowdhury et al., 2014). Phosphorus SFAs range from single city studies (Metson and Bennett, 2015a; Neset et al., 2008) to national (Antikainen et al., 2005; Egle et al., 2014; Klinglmair et al., 2015; Linderholm et al., 2012; Senthilkumar et al., 2014; Smit et al., 2010; Sokka et al., 2004), and multi-country reports (Ott and Rechberger, 2012; van Dijk et al., 2016). These studies examine flows of P from agriculture and imported household products, through the food and waste systems of urban areas to waterways, agriculture, and landfills, showing, for example that up to 50% of P in urban areas ends up in solid waste that is accumulating in landfills (Kalmykova et al., 2012; Ott and Rechberger, 2012). In areas that send their biosolids (or sewage sludge incineration ash) to landfill, the amount of P accumulating in landfills could be even greater (Metson and Bennett, 2015a). However, SFAs of urban areas are often snapshots at a single point in time and do not assess P flows over time or across policy shifts, meaning they are not always up to the task of improving P management policies. Senthilkumar et al. (2014) argue that exploring P recycling options in detail requires additional studies capable of examining food waste and diet habits and dynamically modelling P flows through the food chain.

One concept that may be useful in assessing and improving P management strategies is that of circular economies. The idea of circular economies, which aim to maximize the useful life of resources by increasing recovery and regeneration rates, is gaining traction across Canada, the US, and Europe (European Commission, 2016; Fehrenbacher, 2016; Freeman, 2016). A circular economy approach to P management could replace the existing linear P flow in favour of something with more recycling and slower overall throughput. Recovering and recycling P from anthropogenic waste streams such as wastewater and organic waste provides significant potential to produce a more circular nutrient cycle. Wastewater and organic waste are two of the most promising avenues for P recovery and reuse as they are among the most easily modified by management (Egle et al., 2014; Klinglmair et al., 2015). Such management may include strategies and policy programs that are focused on intercepting P-rich substances such as organic waste, wastewater (e.g. struvite; see Box 1), and biosolids, and returning them to agricultural land.

In Canada and the US, P pollution reduction policies focusing on agriculture and wastewater have been in place since the 1970s (United States Environmental Protection Agency (USEPA) - Environment Canada, 2012). However, policies developed to encourage P recovery through organic waste and biosolids recycling are just beginning to gain prevalence (City of Guelph, 2014; City of Toronto, 2016; Government of Ontario, 2016; Region of Peel, 2009). This trend is mirrored in research where the literature on P removal and even recovery from wastewater is extensive (e.g. Doyle and Parsons, 2002; Mayer et al., 2016; Morse et al., 1998; Yeoman et al., 1988), while limited research has been conducted on P recycling from organic waste (Cordell et al., 2012; Senthilkumar et al., 2014). Much P research to date neglects the organic waste diversion stream (Antikainen et al., 2005; Garnier et al., 2015), either explicitly or implicitly assumes all P contained in diverted organic waste is returned to arable land (Neset, 2005; Theobald et al., 2016), or looks solely at compost applied to land and neglects the link between diversion and application (Cooper and Carliell-Marquet, 2013). With up to 50% of urban P contained in organic waste (Kalmykova et al., 2012; Ott and Rechberger, 2012), more research is needed to better understand the role that organic waste management can play in reducing P pollution and increasing recovery and recycling.

In this study, we develop a system dynamics model for P flows on the island of Montreal. As a foundation, we provide a detailed SFA of present P flows on the island, focusing on the food, wastewater, and waste management sectors. Then, through the use of scenarios quantified via a dynamic P model, we explore how these flows might change over time as a result of impending changes to policy and potential shifts in social behaviour. Beyond simply mapping P flows, we aim to identify the amounts of recoverable P in waste systems under various management scenarios, and where that P can be reused.

2. Case study: Montreal

The island of Montreal is located in the southwestern region of Quebec, Canada on the Saint Lawrence River. The island is administered by 18 municipalities including the City of Montreal and is governed by the province of Quebec, the *Communauté Métropolitaine de Montréal* (CMM; which governs the island as well as several, off-island neighbouring municipalities), the *Agglomération de Montréal* (which governs all municipalities on the island), and by individual municipal councils.

In 2010, the provincial government tabled the *Quebec Residual Materials Management Policy* (Québec, 2010) which requires municipalities to divert 60% of their organic waste and biosolids from landfills by 2015, with 100% of their organic waste diverted by 2020. This policy falls within the *Quebec Provincial Environmental Quality Act* (Québec, 2011), and requires all regional county municipalities (MRCs) and metropolitan communities (such as the CMM), to establish a residual materials management plan in accordance with the government's

Box 1
: Definitions.

Biosolids: The solid fraction of organic matter recovered from wastewater treatment facilities. When treated and processed this material can be used for land application as a fertilizer product to improve and maintain soil.

Organic waste: Biodegradable waste material such as food waste, and leaf and yard waste. It is sometimes referred to as bio-waste, green waste, biodegradable municipal waste (BMW), organic fraction of municipal solid waste (OFMSW), and/or putrescible waste. Herein, *organic waste* refers to solid organic waste and does not include wastewater, sewage, or biosolids. *Organics* refers to both solid organic waste, as well as organic materials in wastewater or produced from wastewater.

Organics: All processed organic material from solid waste and wastewater systems, including organic waste, biosolids, and struvite.

Struvite ($NH_4MgPO_4{\cdot}6H_2O$): A phosphate compound that is often considered a nuisance in wastewater treatment plants, but that can be recovered for beneficial use from these facilities using advanced technology (Mayer et al., 2016). Once recovered, the compound can be used as a fertilizer substitute.

Waste: The by-products, end-products, or materials that are discarded or eliminated at the end of a process. Here, waste can refer to materials that are discarded products from one process, but can be recovered for beneficial use in another process: e.g. food waste, which can be collected and used to produce biogas and soil amendment.