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Scenarios for achieving absolute reductions in phosphorus consumption in Singapore

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ABSTRACT

Phosphorus is a resource that is utilized with efficiency in most parts of the world. Farmers fertilize with increasing precision; wastewater treatment plants strip phosphorus from sewage; and industries make use of phosphorus byproducts. Why, then, do incidents of eutrophication and harmful algal blooms related to excessive phosphorus outflows continue to intensify? Incremental improvements in phosphorus use efficiency and monitoring of individual phosphorus waste streams no longer seem sufficient to dampen these environmental impacts. A radical shift in perspective is needed, one in which phosphorus is treated as a resource rather than as waste. Using substance flow analysis, we explore various types of phosphorus management scenarios for a specific system, for the urban city-state of Singapore. These scenarios are jointly framed with the urban planning agency of Singapore and takes into consideration both behavioral and infrastructural changes to the status quo. These scenarios include strategies and technologies such as composting, separated incineration of organic and non-organic waste, anaerobic co-digestion of food waste and wastewater, and dedicated anaerobic digestion of food waste and wastewater. Publicly available UN Comtrade data is used to establish temporal trends in phosphorus consumption between 1989 and 2012. Phosphorus waste outputs are verified via empirically collected data on household and commercial waste generation. The results of this paper demonstrate how the transition from a linear to a closed-loop phosphorus cycle might be possible for Singapore, an island that is an important test bed for planning the sustainable metabolism of future urban areas.

1. Introduction

Phosphorus is a finite substance whose function is irreplaceable (Syers et al., 2008; Jasinski, 1999). While phosphorus remains a relatively abundant material on earth, its critical role in both natural and human-made ecosystems makes the continued, uninterrupted access to this substance crucial. Though phosphorus is mostly associated with agriculture and its use as a fertilizer, mined phosphate rock can also be processed to be used in food products, detergents, toiletries, and industrial chemicals (JDC, 2014; Köhler, 2006; Van Drecht et al., 2009). As a result, as it is in the case of Singapore, an understanding of the urban phosphorus cycle is a key part of mitigating eutrophication events and other symptoms of excessive phosphorus output into the natural environment.

Though it is an element that is theoretically recycled on geological time scale from marine sediment to the lithosphere (Smil, 2000), anthropogenic use of the substance is depleting the supply at rates which outstrip the sedimentation of phosphorus (Sharpley et al., 1995; Bouwman et al., 2009; Morée et al., 2013; Smil, 2000; Mackenzie et al., 2002). The main source of phosphorus is in phosphate rock (Jasinski, 1999; JDC, 2014; de Ridder et al., 2012). 72% of phosphate production in 2014 was found in the United States, China, and Morocco (Heckenmüller et al., 2014; de Ridder et al., 2012; IFA, 2013; Van Kauwenbergh, 2010).

Anthropogenic use of phosphorus has led to an excess output of the substance into the environment and has degraded freshwater and marine water quality around the world in the past decades (Bennett et al., 2001; Carpenter et al., 1998). Researchers have assumed that agricultural run-off is the main source of this excessive phosphorus burden. Consequently, most phosphorus management strategies have focused on how farmers can implement changes to reduce phosphorus inputs and increase phosphorus use efficiency (Sharpley et al., 2003; Sharpley, 1995; Nelson and Shober,

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2012; Sharpley et al., 2013; Kronvang et al., 2007). A recent review of the literature reveals, however, that phosphorus is used more efficiently in agriculture than is commonly believed. Syers et al. (2008) showed that the efficiency of applied fertilizer ranged between 50% and 90% (Johnston and Syers, 2009; Syers et al., 2008). Scientists are developing crop breeds with higher yield per unit of phosphorus taken up (phosphorus use efficiency, PUE) (Veneklaas et al., 2012). While phosphorus use efficiency is still low in developing countries (Zhang et al., 2007), farmers are fertilizing with increasing precision, especially in the developed world (Schröder et al., 2011; Grisso et al., 2011; Phillips, 2007).

Despite improvements in the agricultural sector, intensification of eutrophication and harmful algal blooms events related to excessive phosphorus outflows in the U.S. and other developed countries have persisted (Diaz and Rosenberg, 2008; Selman et al., 2008; Andersen and Conley, 2009; Rabalais et al., 2009). In the waters around Singapore, for example, eutrophication and harmful algae blooms have become a recurring problem only in the past several years (Lee, 2014; Imai et al., 2006; Gin and Gopalakrishnan, 2009; Biswas et al., 2009). Each event has resulted in hundreds of thousands of dollars of damage for fisheries who rely on the local water quality for aquaculture operations (Salleh, 2014). In the U.S., Lake Eerie has also experienced some of the worst toxic algae blooms in history in recent years, leading to species mortality, decreased tourism, and a decline in water quality (Wines, 2013; Charlton, 2008).

One hypothesis for why these events are occurring is that the vast amount of phosphorus consumed by industry, businesses, and households located in non-agricultural areas has been overlooked in the search for solutions to addressing eutrophication and toxic algae blooms (Hatt et al., 2004; Fissore et al., 2011; Baker et al., 2006; Jarvie, NEAl, and Withers, 2006; Jarvie et al., 2013; Millier and Hooda, 2011). Calculations made by the authors based on existing data show that phosphorus in human excreta, the main source of phosphorus outflows from urban areas and human settlements, represents 17% of the total amount of phosphorus rock that is mined each year (Van Kauwenbergh, 2010; Smil, 2000; Cordell et al., 2009). This does not include industrial uses of phosphorus (presumably for urban use) and phosphorus in organic solid waste, which increases this percentage to 34%. Therefore, we see a significant opportunity in capturing these flows to bolster the phosphorus supply. This phosphorus is lost through wastewater effluent, leachate in landfills, soil or storm run-off. Reviewing all published phosphorus balances for urban systems shows that phosphorus is discharged into the environment after a single use and rarely recovered (Yuan et al., 2011a,b; Metson et al., 2012; Baker, 2011; Pearce and Baker; Nilsson, 1995; Færge et al., 2001; Warren-Rhodes and Koenig, 2001; Liu, Chen, and Mol, 2004; Liu et al., 2013; Kalmykova et al., 2012; Schmid Neset et al., 2008). Other studies have suggested that wastewater effluent from urban settlements are an overlooked source of phosphorus output into water bodies (Jarvie et al., 2013; Jarvie, NEAl, and Withers, 2006; Reynolds and Davies, 2001; Van Drecht et al., 2009; Mihelcic et al., 2011).

This paper suggests that cities present both a challenge and an opportunity for creating a more sustainable phosphorus flow in the future. Cities, unlike diffuse non-point sources of phosphorus run-off from agricultural sources, are ideal places to pilot phosphorus recovery projects. Phosphorus output is relatively concentrated in large quantities so they provide the best conditions for the implementation of recovery technologies. Only when phosphorus is treated as a resource rather than as waste can absolute reductions in phosphorus be made. That is, when the focus is no longer on limiting the concentration or total load of phosphorus flowing to water bodies, but rather, on how phosphorus can be recovered for re-use.

This study differs from previous phosphorus balances in three ways. First, this study measures the phosphorus flux over a twenty-three year period for Singapore, presenting a dynamic view of the phosphorus balance over time. All but two existing studies (Han et al., 2011; Warren-Rhodes and Koenig, 2001) provide a static snapshot of the phosphorus balance.

Second, due to the availability of United Nations (UN) Comtrade data (available only for countries, and not cities), this study is able to include a more comprehensive list of phosphorus sources. Singapore, for this reason, is an ideal system for carrying out such a phosphorus balance. Due to lack of data, almost all other studies on the city-scale use per capita consumption proxies to estimate the total amount of food and detergent inputs into a system. Consequently, researchers have to determine, a priori, the important sources of phosphorus. These assumptions may eliminate possible important sources of phosphorus, such as rubber, chemicals, and slag, leading to an incomplete phosphorus balance. Also, for cities without UN Comtrade data, calculating the total input of phosphorus for a region from per capita consumption may lead to large margins of error, since per capita values are averages and may not reflect the true nature of phosphorus consumption in an area. UN Comtrade data is available for Singapore and is ideal for studying substance flows at a city-scale.

Third, this study differs from other phosphorus balances by focusing on exploring differences in phosphorus recovery strategies, rather than increasing phosphorus efficiency or changing diets as scenario developments. This means that a criterion for selecting intervention options is they lead to absolute reductions in phosphorus throughput, rather than merely incrementally decreasing phosphorus consumption. In this study, we use the results of the Substance Flow Analysis (SFA) to explore a business-as-usual (BAU) scenario, as well as three other phosphorus management (recovery) scenarios for one specific system, the urban city-state of Singapore. These scenarios are differentiated based on the level of infrastructural investment necessary for implementation and the diversity of by-products that results from recovery strategies.

Singapore represents a developed economy that many emerging, fast-growing cities in the world, especially in Asia, are modeling. Singapore is therefore an important, though often overlooked, test bed for planning the sustainable metabolism of future urban areas. As an island, the nation also presents an important opportunity for understanding urban metabolism by offering a clear system boundary for analyzing inputs and outputs of substances. For this paper, we deepen our understanding of urban metabolism through the lens of phosphorus flows using substance flow analysis (SFA) as the methodology.

2. Approach

This study takes an interdisciplinary approach towards understanding the phosphorus balance of Singapore and has a dual purpose. First, the aim is to understand the quantity and quality of current and past phosphorus flows in Singapore. Second, the aim is to use this information to construct and compare various phosphorus management scenarios in the future. To this end, this study relies on a substance flow analysis (SFA) and mass balance framework to calculate the input, output, and accumulated amounts of phosphorus within Singapore.

SFA methodology is a process of evaluating the mass balance of a substance across a particular system boundary. The process of accounting for all the sources, end-uses, and fates of the material of interest allows the researcher to gain a systems-level understanding of how efficiently the material is used, how much material is used, and which sectors are more dependent on the particular

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