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Urban phosphorus sustainability: Systemically incorporating social, ecological, and technological factors into phosphorus flow analysis

Geneviève S. Metson [a,*], *David M. Iwaniec* [b], *Lawrence A. Baker* [c], *Elena M. Bennett* [a], *Daniel L. Childers* [d], *Dana Cordell* [e], *Nancy B. Grimm* [b,f], *J. Morgan Grove* [g], *Daniel A. Nidzgorski* [h], *Stuart White* [e]

[a] *Department of Natural Resource Sciences and McGill School of Environment, McGill University, 21,111 Lakeshore Road, Sainte-Anne-de-Bellevue, QC, Canada*
[b] *Julie Ann Wrigley Global Institute of Sustainability, Arizona State University, Tempe, AZ 85287-5402, USA*
[c] *Department of Bioproducts and Biosystems Engineering, University of Minnesota, 1390 Eckles Avenue, St. Paul, MN 55108, USA*
[d] *School of Sustainability, Arizona State University, Tempe, AZ 85287-5502, USA*
[e] *Institute for Sustainable Futures, University of Technology Sydney, P.O. Box 123, Broadway, NSW 2007, Australia*
[f] *School of Life Sciences, Arizona State University, Tempe, AZ 85287-4501, USA*
[g] *US Forest Service, Northern Research Station, Baltimore, MD, USA*
[h] *Ecology, Evolution, and Behavior, University of Minnesota, 1987 Upper Buford Circle, St. Paul, MN 55108, USA*

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ABSTRACT

Phosphorus (P) is an essential fertilizer for agricultural production but is also a potent aquatic pollutant. Current P management fails to adequately address both the issue of food security due to P scarcity and P pollution threats to water bodies. As centers of food consumption and waste production, cities transport and store much P and thus provide important opportunities to improve P management. Substance flow analysis (SFA) is often used to understand urban P cycling and to identify inefficiencies that may be improved on. However, SFAs typically do not examine the factors that drive observed P dynamics. Understanding the social, ecological, and technological context of P stocks and flows is necessary to link urban P management to existing urban priorities and to select local management options that minimize tradeoffs and maximize synergies across priorities. Here, we review P SFA studies in 18 cities, focusing on gaps in the knowledge required to implement P management solutions. We develop a framework to systemically explore the full suite of factors that drive P dynamics in urban systems. By using this framework, scientists and managers can build a better understanding of the drivers of P cycling and improve our ability to address unsustainable P use and waste.

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[*] *Corresponding author*. Tel.: +1 438 823 2027.
E-mail addresses: genevieve.metson@mail.mcgill.ca (G.S. Metson), diwaniec@asu.edu (D.M. Iwaniec), baker127@umn.edu (L.A. Baker), elena.bennett@mcgill.ca (E.M. Bennett), dan.childers@asu.edu (D.L. Childers), dana.cordell@uts.edu.au (D. Cordell), nbgrimm@asu.edu (N.B. Grimm), jmgrove@gmail.com (J.M. Grove), dnidz@umn.edu (D.A. Nidzgorski), Stuart.White@uts.edu.au (S. White).

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1. Introduction

1.1. *The importance of phosphorus to society*

Massive changes in Earth's biogeochemical cycles have been driven by human activity (Schlesinger and Bernhardt, 2013). Changes in phosphorus (P) cycling increasingly require active management to address problems of both excess (aquatic pollution, Carpenter et al., 1998) and scarcity (lack of P hinders agricultural production and thus food security, Childers et al., 2011). Concerns about P scarcity in the global food system and pollution of waterways have led to an improved understanding of P-related problems and movement toward potential solutions. Frameworks to explain P movement in agricultural areas (MacDonald et al., 2011) and as a result of global agricultural trade (Schipanski and Bennett, 2012), as well as vulnerability assessments at national (Cordell and Neset, 2014) and regional scales (Cordell et al., 2011) have helped bridge the gap between our understanding of anthropogenic P cycling and actions that can be taken to more sustainably manage the resource.

To manage P sustainably, we clearly need an accurate understanding of where P is stored (i.e., stocks or pools) and how it moves through a system (i.e., flows). Completing a substance flow analysis (SFA, Baccini and Brunner, 1991; Brunner and Ma, 2009) can help researchers and managers identify inefficiencies that might be problematic from a resource management standpoint by quantifying inputs, outputs, internal cycling, and storage. Such analyses can be applied to any system in which P moves or transformations occur, such as a watershed (Likens, 2013) or city (Kennedy et al., 2010).

However, SFA information alone may not be enough to instigate change in P management. While SFAs are often used to understand P cycling and are a useful tool, they do not inherently provide information about the system of factors (and actors) that drive P stocks, flows, and management. As such, the results of SFAs are not always easily applied to decision-making, especially in complex urban ecosystems.

1.2. *The importance of driving factors*

To fully utilize the information SFAs provide to inform sustainable P management, we need to understand which factors directly and indirectly drive P flows and how these drivers are connected to one another. Understanding factors that drive changes in ecosystems, as well as their linkages, is a key component of designing interventions that are desirable in the long term (Alcamo and Bennett, 2003). By considering the constellation of factors that drive complex problems such as P (Metson et al., 2013), it becomes possible to see how indirect drivers of P may also be involved in the management of other resources, and thereby link P management to existing urban priorities and plans. This approach has been used to bridge theory about the management of a problem to changes in practice in many fields (e.g., natural resource management (Bosch et al., 2007) and public health (Luke and Stamatakis, 2012; Sterman, 2006)). Such higher-level thinking about the system can also help create a shared understanding to overcome barriers to the implementation of solutions (Meadows and Wright, 2008). In other words, P management is more likely to succeed if P sustainability is shown to be relevant and salient to other stakeholder (including municipal) priorities (Lang et al., 2012; Talwar et al., 2011).

In addition to allowing researchers to see how P cycling is linked to existing priorities and plans, explicitly considering the relationships among factors that drive P cycling may facilitate the identification of solutions that minimize tradeoffs and maximize synergies with other plans. By explicitly considering causal links, feedbacks, and time lags among driving factors, such systems thinking may encourage P management options that effectively transform problematic P dynamics. Meadows and Wright (2008) refer to two different types of solutions: *low-level* and *high-level solutions*. Similarly, Childers et al. (2014) discuss solutions to urban problems that merely *tweak* the current system versus those that *transform* cities. In both cases, the authors suggest that a deep understanding of the different components (driving factors) of a system and their linkages is necessary to develop solutions that maximize desirable system transformations and minimize unintended, negative, small or large changes. In the case of P management, we would want to select solutions that decrease contributions to scarcity and pollution at many scales, while synergizing with other non-P urban management priorities such as waste management.

Bridging the gap between scientific understanding and policy relevance has been part of the sustainability discourse for the past decade (Kates et al., 2001). Through this conversation, scientist have learned that in order to create change, it is not sufficient to only understand the particular sustainability challenge and propose solutions; one must also explicitly take into consideration the policy and management context surrounding that challenge (Turnhout et al., 2007). When the governance of natural resources becomes increasingly decentralized and adaptive to better address the complex nature of natural resource management challenges, scientists need to create knowledge with a diverse group of stakeholders to increase the robustness, legitimacy, and relevance of their work (Folke et al., 2005). The necessity to increase the relevance of natural resource management and sustainability science by engaging with stakeholders has been demonstrated in ecological economics and through the use of indicators (Hezri and Dovers, 2006) in water management (Lach et al., 2005) and in conservation (Ryan and Jensen, 2008). Research at the science-policy interface is important to foster sustainable resource and ecosystem management and requires systems approaches that account for the various needs, roles, and actions of actors and institutions (Innes and Booher, 2000; Fisher et al., 2009).

1.3. *Urban ecosystems and P*

P studies and management often focus on agricultural systems; however, cities, with their extensive demand for products and production of vast amounts of waste, are hotspots for P cycling. There is thus an opportunity for cities to play an important role in addressing the local and global environmental challenges of P management. However, few P studies have focused on urban ecosystems, and those