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

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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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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 trade-offs 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

primarily quantified stocks and flows of P in cities without addressing the higher-level drivers of these stocks and flows. As such, we have only a rudimentary understanding of the factors that drive P dynamics in cities, factors that, according to Meadows and Wright (2008) and Childers et al. (2014), will make the difference between tweaking and transforming the system.

Cross-city syntheses have found that the main inflows of P to urban environments are related to food, and the outflows related to wastewater, while the main storage pools occur in landfills (Chowdhury et al., 2014). There are, however, differences in the magnitude of P flows among cities (Kennedy et al., 2010). Because each city is characterized by a unique context (Grimm et al., 2008), the specific P dynamics of a city vary as do the factors (and potential interventions) that drive those P dynamics.

2. Framework development

As a first step toward making urban P SFAs more relevant to urban decision-making and implementation of sustainable urban P solutions, we present a framework to help researchers include the higher-level social, ecological, and technological factors that drive urban P cycling. By identifying driving factors and exploring the relationships among the factors influencing P cycling, researchers will be able to: (a) broaden the range of potential interventions considered; (b) better understand how planned and unintended changes can affect P sustainability and overall urban sustainability; and (c) elucidate systemic linkages to municipal priorities in order to increase our ability to engage with decision-makers. Our framework, described in Section 3, is based on a comprehensive synthesis of existing literature (publications on SFA of P from 18 international cities), combining the information gaps identified by P SFA authors (Section 2.1) and the implicit driving factors used to calculate P SFAs (Section 2.2).

2.1. Author-identified gaps

We examined the literature for author-identified gaps that limit the ability of P SFA results to direct policy change in P management (20 studies across 18 cities; Table 1). To identify relevant studies, we performed a Google Scholar search with the keywords "urban", "city", "phosphorus", and "flow analysis". We then scanned the literature cited in these articles to ensure we had not missed any relevant material. For each article, we identified factors that the SFA authors identified as important considerations for decision-making and solution implementation that their research did not explicitly address.

The authors of these 20 studies identified a diverse set of knowledge gaps that impede our understanding of urban P cycling and its application to management. Identified knowledge gaps included: The importance of gaining cultural acceptance of proposed solutions (eight studies); understanding of consumer/resident behaviors and choices (five studies); knowledge of how stakeholder priorities affect future P cycling (two studies), and; understanding how P management interacts with other urban goals to cause synergies or tradeoffs, especially water- and energy-related priorities (eight studies;

see Table 1 for citations and details). The authors of seven studies mentioned the need for cost assessments of management and recycling options, while five studies mentioned the logistics of implementing recycling options. Understanding change over time was also highlighted by several papers, including discussions of legacies to current P cycling (two studies) and the importance of considering changes in urban development patterns and plans (eight studies). Similarly, understanding how cities link to different geographical or decision-making scales was an important theme (10 studies).

Our review of author-identified knowledge gaps in current P SFA analyses highlights the need for a structured and systemic approach to identifying locally relevant factors driving urban P dynamics. From our review, it is clear that a wide range of driving factors need to be understood at multiple interacting spatial and temporal scales. Global (e.g., global P supply), national (e.g., capital, cultural, and legal factors), municipal (e.g., urban–rural linkages), and households and individual (e.g., willingness to pay and behaviors) factors were all mentioned more than once, as were legacy (e.g., urban form and sewage infrastructure lock-in), current issues (e.g., eutrophic ecosystems), and the future (e.g., municipal goals and plans). Occurring at many spatial and temporal scales, these factors are not operating in isolation and in order to understand them, we need to understand causal linkages and relationships between factors.

Multiple studies discussed the need to understand stakeholders perspectives and goals and the logistical and economic implications of management options at multiple scales, and identified three other gaps: (1) six studies identified the need to manage multiple resources at once (and thus understand how they interact); (2) one study underlined the need to plan for unintended consequences of management options; and (3) another study emphasized the need to take a holistic approach to waste management. All three of these themes require both researchers and managers to understand causal linkages.

2.2. Implicit factors

In calculating P SFAs, some social, ecological, and technological drivers are already being considered, albeit implicitly. Making these drivers explicit will help improve the usefulness of SFA for decision-makers. For example, to calculate the amount of P entering a city as food, a researcher might multiply total population by per capita food consumption (quantity and types of food), and the P content of those food items. Implicit in that calculation are factors such as income, accessibility of food, and cultural preferences that affect dietary choices and consumption. On the outflow side of the urban system, calculating P leaving the city through waterways may involve multiplying the proportion of the population served by wastewater treatment plants by their level of treatment or P content of outflowing water. Such a calculation may also include losses from runoff, erosion, and untreated sewage waste for proportions of the area (and/or population) that are not covered by centralized sewage. These calculations implicitly require details about city infrastructure for sanitation (e.g., sewage connections, level of treatment, and water use) and land use. While not usually explicitly discussed,

Table 1 – Additional knowledge needs identified by existing phosphorus (P) substance flow analysis (SFA) paper authors. Authors (column 2) have conducted P SFA studies in 18 cities (column 1), evaluated different components of the urban P cycle (column 3), and identified areas where more information or understanding is necessary (column 4). Specifically, the fourth column contains knowledge gaps mentioned by authors, largely in their "discussion" and "future work" sections, as important factors needed to implement solutions but not explicitly considered in the construction and analysis of their P SFA.

City	Authors	P flows considered	Author(s) identified what other considerations need to be included to implement solutions and for decision-making
Arba Minch, Ethiopia	Meinzinger et al. (2009)	Food subsystem	-Logistics of waste collection (including transportation) -Cost assessment (among the different waste recycling solutions) -Cultural acceptance of the solutions -Trade-offs with other resources (water use and water-based toilets) -Synergies with other urban goals (sanitation improvements)
Bangkok, Thailand	Faerge et al. (2001)	Food subsystem	-Linkages between urban and rural P cycling -Unintended consequences of potential solutions -Future urbanization patterns and plans (Masterplan for the city)
Beijing, China	Han et al. (2011)	Whole system (using net anthropogenic P accumulation over time)	-Knowledge about P management (educate farmers about fertilizer application) -Future urbanization patterns and plans (including demographic changes and resulting changes in food demands, waste production and infrastructure)
Beijing and Tianjin, China	Qiao et al. (2011)	Food subsystem	-Linkages between urban and rural P cycling -Cost assessment (among the different waste recycling solutions and food import and production) -Knowledge about P management (educate urban decision-makers) -Cultural acceptance of the solutions (biosolid use) -Synergies and trade-offs with other urban goals (pollution reduction, human health, and water scarcity)
Chaohu, China	Yuan et al. (2011)	Food subsystem	-Temporal change (historical record and legacy of P dynamics, continued monitoring) -Cross-scale dynamics (regional and global trade relationships and pollution as an externality) -Site-specific considerations for P recycling and conservation options (feasibility of buffer-zones and use of organic-based fertilizers)
Galve, Sweden	Nilsson (1995)	Food and timber subsystems	-Cross-scale dynamics (international trade) -Cost assessment (among waste recycling and infrastructure solutions) -Willingness to pay (for solutions) -Economic responsibility (who pays for solutions?) -Cultural acceptance of solutions and environmental state (it might be acceptable to have eutrophic water bodies?) -Trade-offs with other urban goals (combined waste systems can be easier for management but problematic for recycling)
Gothenburg, Sweden	Kalmykova et al. (2012)	Whole system	-Cross-scale dynamics (local to global relationships and differences) -Cultural acceptance (perception of contamination in recycled products and recycling of waste in general) -Synergies and trade-offs with the management of other resources (stoichiometry of possible recycled products) -Holistic and systems approaches to waste policy (not just focused on wastewater solutions)
Hanoi, Vietnam	Montangero et al. (2007)	Food system	-Logistics of waste recycling (how to alter the sanitation system to concentrate P) -Cost assessment (among potential solutions) -Willingness to pay (for solutions) -Legal and institutional framework -Stakeholder priorities, needs, and demands -Synergies and trade-offs with other urban goals (health impact of management options) -Future fertilizer demand (based on demographics and site-specific fertilizer needs for local and surrounding agriculture)
Harare, Zimbabwe	Gumbo et al. (2002)	Food and water subsystem (focused on household)	-Logistics of waste recycling (technological constraints of solutions) -Cultural acceptance of solutions -Synergies and trade-offs with other urban goals (health impacts of management options) -Future urbanization plans (including stakeholder perspectives on city planning and design)

Table 1 (*Continued*)

City	Authors	P flows considered	Author(s) identified what other considerations need to be included to implement solutions and for decision-making
Heifi, China	Li et al. (2011)	Whole system	-Temporal change (over-enrichment of soils and long-term effects on aquatic systems because of agricultural practices) -Climate -Resource availability (P mining) -Consumer behaviors (diet, detergent, and other household items) -Stakeholder priorities (government commitment to issues through policy change) -Knowledge about P management (environmental education) -Synergies and trade-offs with the management of other resources (energy)
Hong Kong, China	Warren-Rhodes and Koenig (2001)	Whole system (part of a larger metabolic study of the city over time)	-Temporal change (check changes in patterns and drivers, including consumption patterns, and evaluate the effectiveness of policies) -Stakeholder priorities and knowledge (integration of scientific knowledge into government management, making water pollution a priority)
Kumasi, Ghana	Leitzinger (2001)	Food and timber (focus on urban agriculture)	-Cost assessment (among waste recycling solutions) -Willingness to pay (for recycled P products) -Legal framework -Cultural acceptance of solutions (use of compost by farmers, concerns about heavy metal contamination)
Linkoping, Sweden	Neset et al. (2008)	Food system (historical)	-Legacies and lock-ins (associated with wealth e.g., existing sewage infrastructure as a barrier to recycling) -Cross-scale dynamics (global agricultural trade) -Cultural preferences (western lifestyles and meat consumption) -Future urbanization patterns and plans (including demographics and land use change)
Montreal, Canada	Metson and Bennett (2014)	Food system (focus on urban agriculture)	-Knowledge about P management (citizen, NGO, and government understanding of balanced P application and different sources of P) -Cultural acceptance of solutions (use of compost by farmers and urban agriculture practitioners) -Future urbanization plans (including urban agriculture priorities and city management and planning) -Logistics of waste recycling (matching technologies and guidelines to particular on- and off-island agricultural practices)
Phoenix, USA	Metson et al. (2012a)	Whole	-Spatially explicit (land-use pattern, arrangement, and proximity of sources and sinks) -Cross-scale dynamics (price and availability of resources locally are determined at larger scales) -Cost assessment (among waste recycling solutions) -Consumer behavior (diet and fertilizer use) -Knowledge about P management (partnership and co-creation with practitioners, and awareness of P issues) -Synergies and trade-offs with the management of other resources (elements, water, and energy)
Phoenix, USA	Metson et al. (2012b)	Agriculture and waste	-Legacies and lock-ins (associated with wealth e.g., land use and waste management technology) -Cross-scale dynamics (price and availability of resources locally are determined at larger scales) -Spatially explicit (land-use pattern, arrangement, and proximity of sources and sinks) -Cost assessment (among waste recycling solutions) -Consumer behavior (diet and fertilizer use) -Knowledge about P management (partnership and co-creation with practitioners, and awareness of P issues) -Stakeholder priorities (heterogeneity of perspectives among water, waste, and agricultural management) -Synergies and trade-offs with the management of other resources (elements, water, energy, and land use/land cover, fertilizer, and cost of these resources) -Synergies and tradeoffs with other urban goals

Table 1 (*Continued*)			
City	Authors	P flows considered	Author(s) identified what other considerations need to be included to implement solutions and for decision-making
Stockholm, Sweden	Burstrom et al. (1997)	Whole	-Consumer behavior (lifestyle choices that cannot be changed solely by city managers e.g., diet) -Governance of environmental management (adopt a more pro-active approach) -Stakeholder priorities (heterogeneity of perspectives, development of a shared vision) -Future urbanization plans (Agenda 21 goals and priorities)
Sydney, Australia	Tangsubkul et al. (2005)	Whole (focus on wastewater)	-Temporal change (dynamic modeling) -Cost assessment (among potential solutions) -Synergies and trade-offs with the management of other resources (prioritize objectives P and wastewater objectives)
Twin Cities (Minneapolis/ Saint-Paul, USA)	Baker (2011)	Whole	-Cross-scale dynamics (links of city to larger scales) -Linkages between urban and rural P cycling (including transportation cost) -Logistics of waste recycling (scalability of solutions) -Consumer behavior (diet choices)
Twin Cities (Minneapolis/ Saint-Paul, USA)	Fissore et al. (2012)	Whole (Household fluxes)	-Spatially explicit (P hotspots e.g., from pet waste) -Site-specific considerations for P recycling and conservation options (integrated social, ecological, and, economic considerations)

important information about factors regulating P flows is often implicit within SFA calculations. Explicit consideration of these factors will allow us to consider the role of higher level and indirect driving factors that may be related to other urban priorities, thus promoting more effective interventions.

3. Framework

Based on our assessment of the gaps in 18 cities with SFAs and the implicit factors hidden in SFAs, we identified eight highly interconnected categories that encompass the broad suite of social, ecological, and technological factors that drive urban P cycling. While specific factors in each category, as well as the relationships between factors, may be unique to each city, the broad categories encapsulate the wide range of factors across all 18 cities. Evaluating these categories and their interactions through our framework may spark emergent, novel, and unexpected solutions for P decision-making and interventions.

3.1. Categories of driving factors

For each category (Fig. 1) we provide a generalized definition and examples illustrating its salience and relevance to P management, through examples from the 18 cities included in our literature review:

- *Biogeophysical situation* comprises the biological, geological, and physical factors that affect the urban area. For example, P dynamics associated with atmospheric deposition, storage in soils, and through waterways may be strongly regulated by the local biophysical context, as illustrated by the city of Phoenix, USA. This desert city has high soil calcium carbonate concentrations facilitating P storage, and its arid climate (high evapotranspiration and low precipitation) and few large water bodies regulate the relatively small losses of P through waterways (Metson et al., 2012a). These biophysi-

cal features also influence other aspects of urban management, such as water management (e.g., promotion of drainage in wet climates; water reuse in arid climates), which in turn affect P cycling. Low water availability and aridity in Phoenix also influence decision-making about water recycling infrastructure and policies, which in turn will affect P management.

- *Infrastructure and land use* includes the physical facilities (e.g., roads, pipes, buildings, and retention basins) and characteristics, use, and structure of land (e.g., residential, industrial, commercial). Land use differentiates activities that have distinct, characteristic P flows (e.g., fertilizer application for agriculture or sewage exports from residential areas), and thus land use composition strongly affects overall flows of P. The largest P input to Bangkok, Thailand was food for the urban population, but P flows associated with local food production in rice paddies and freshwater fish production were also significant (Faerge et al., 2001). In cities in Ghana, the close proximity of agricultural and residential land uses enables the transport of P in food to consumers and the reuse of high-P waste from consumers to farmers in community-scale projects (Drechsel et al., 2010). Infrastructure can direct flows of P by affecting the dissemination of inputs to the city, flows within the system, and exports from the city. For example, the lack of centralized sewage treatment in Bangkok, Thailand explains the high P exports to the Chao Praya River and low P retention within the city (Faerge et al., 2001). In contrast, the existing centralized sewage infrastructure in Linkoping, Sweden precludes drastic alterations to P flows in the waste system (Neset et al., 2008). Incineration of solid waste (including organic waste) and subsequent landfilling of ash in Gothenburg, Sweden creates a sink of P that is currently not reused (Kalmykova et al., 2012).

- *Market and capital availability* encapsulates the supply and demand of goods containing P or related to P management, which includes individual, group, and global purchasing
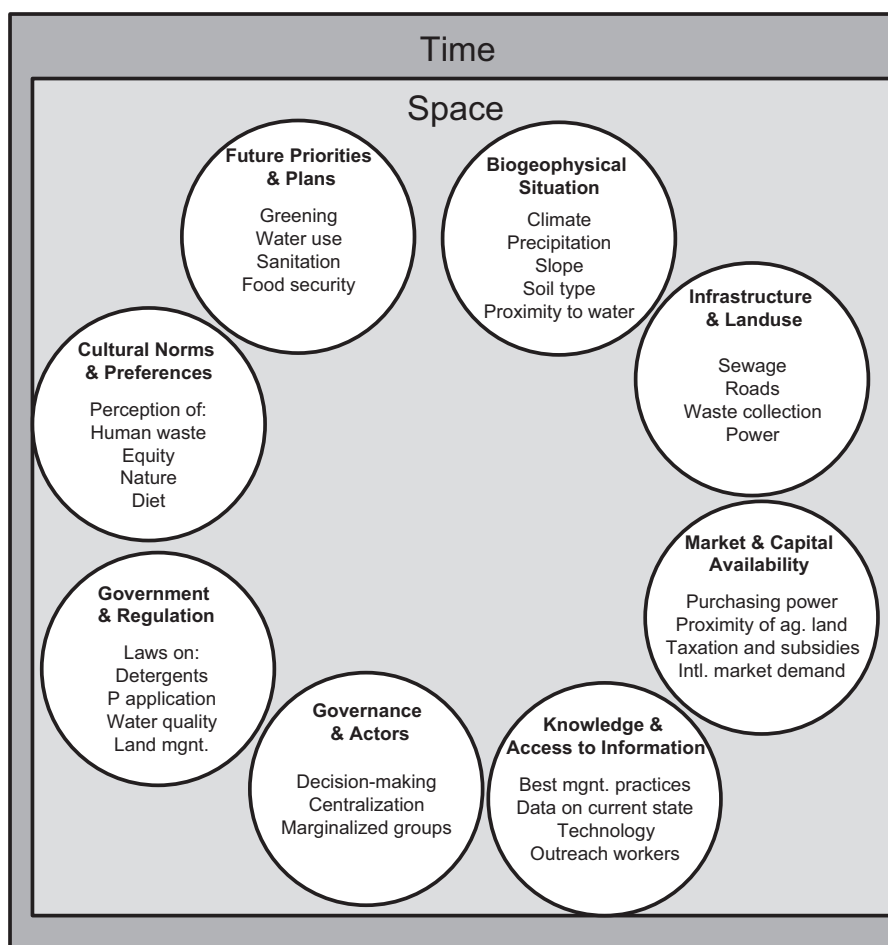
Categories and cross-scalar context

Fig. 1 – Categories of social, ecological, and economic factors that affect urban P stocks and flows and examples of specific driving factors to consider for each category. The Time and Space boxes in figure represent the importance of cross-scalar context that can be relevant to a factor in any category (e.g., a factor may "originate" from a different geographical location or may be the result of a temporal legacy). Factors within and across categories are linked to one another, and that in some cases a factor may map to more than one category.

power, as well as the physical supply and demand of goods. In particular, economic factors affect access to food and fertilizer for the city, and also affect the capacity to sell food, other P containing goods, and alternative fertilizers originating from the city. For example, Leitzinger (2001) mentioned that nearby urban farms in Kumasi, Ghana looking for cheap fertilizer have created a local market for the reuse of chicken manure. However, limited purchasing power in this region constrains development of an economically feasible compost program using human waste (Drechsel et al., 2010). In Chaouhu City, China, P fertilizer application estimates were based on farmer income (Yuan et al., 2011), and in Bangkok, Thailand, income was used as a basis to estimate P intake through diet (Montangero et al., 2007), illustrating the importance of implicit economic factors. In a global market context, the harvest and export of paper and pulp products explains a key P export from Galve, Sweden (Nilsson, 1995). These examples illustrate how purchasing capacity and local, regional, and global

markets can affect inputs, outputs, and internal flows of P in urban areas.

- *Knowledge and access to Information* refers to the quality and quantity of available data and knowledge about infrastructure and decisions related to P management, as well as the mechanisms and capacity to collect, disseminate, and receive information. For example, in Phoenix, USA, when P fertilizer prices increased in 2008, farmers in the area consulted agricultural extension officers for advice on methods to minimize their use of P fertilizers without reducing yield (Metson et al., 2012b). Han et al. (2011) suggested that increasing farmers' knowledge about proper fertilizer application rates, based on the best scientific information available (including amount and timing of fertilization, and soil properties), was an effective way to decrease downstream pollution around Beijing, China. In addition to requiring knowledge for better management within cities, most studies we reviewed explicitly mentioned the need for more data and long-term monitoring to

improve knowledge of urban P flows. Access to information is important to understanding how decisions are being made, but is distinct from the process of decision-making itself (Arnstein, 1969). Knowledge combines with other considerations (cultural preferences, financial capacity, political power) to form legal or informal decisions and actions in the system. As such, the actors who have knowledge networks (formal and informal) through which they can disseminate information must also be fully considered (see subsequent *Governance and Actors* category).

- *Governance and actors* are the individuals and institutions that have responsibilities and legitimacy in decision-making about P driving factors. Identifying both those who are making decisions that affect P cycling and those who are affected by those decisions is key to implementing change in P management. Many decisions that ultimately impact P dynamics may be made outside, or in spite of, existing regulations, requiring researchers to identify "informal" actors or network of actors. For example, household decisions about food, pets, and organic waste management were central to understanding P cycling in Minneapolis/Saint-Paul, USA (Fissore et al., 2012). Although regulations ban P fertilizer on lawns in the city and the landfilling of organic waste, some households continue to use fertilizer and dispose of yard waste through municipal trash collection and these practices, not just regulations, drive P cycling in that city (Baker, 2011).
- *Government and regulation* are the rules, regulations, and mechanisms of enforcement about how we manage land, resources, and waste. In the Minneapolis/Saint-Paul, USA example, local municipal law banning the input of yard waste into landfills and state laws banning the use of P in detergents have reduced P exports to landfills and rivers (Baker, 2011). In Phoenix, USA, over-application of P on agricultural soils can be attributed in part to national Environmental Protection Agency laws on nutrient application that are based on the local limiting nutrient—which is nitrogen in Phoenix—(Metson et al., 2012). The absence of a rule or regulation clearly has an impact of P cycling. Understanding the current regulatory framework helps contextualize current P dynamics, and points toward pathways that may enhance P sustainability (e.g., avoiding landfilling), or may detract from it (e.g., regulation that focuses only on the limiting nutrient).
- *Cultural norms and preferences* are the individual and community views and beliefs about our relationship to nature and natural resources, as well as to other humans through rights and responsibilities of individuals, communities, and governments. Links between cultural norms and preferences and P dynamics occur through dietary choices and waste management strategies. For example, in Chaohu, Beijing, and Tianjin, China, direct recycling of human excreta to local agriculture is a current practice (although it is declining as urbanization increases), and China has a long history of this 'night soil' practice (Qiao et al., 2011; Yuan et al., 2011). In contrast, negative perceptions of the reuse of human urine and excreta are often cited as a barrier to increasing P recycling in Western countries (Childers et al., 2011; Drangert, 1998). Cultural values and perceptions should be considered because they often define the acceptability of technological and systems-level management options (Cochrane, 2006). Although

cultural norms are often slow to change, they are still malleable over longer times scales or may shift rapidly with large social, ecological, or technological changes (Pahl-Wostl et al., 2008).

- *Future priorities and plans* are the government, industry, and community (at many levels) plans for the future. More specifically, one should consider their development plans, implementation of policies, technologies, and principles, or pilot projects and other forms of earnest exploration that may not yet be part of formal planning documents. Linking P management to existing plans and interventions is especially important in order to engage urban decision-makers with potential sustainable urban P solutions, acknowledging goals may vary widely across cities. For example, co-composting plans for wastewater biosolids and solid organic waste in Kumasi, Ghana are being explored to improve sanitation and increased food security (Leitzinger, 2001). In Sydney, Australia, concerns about future seasonal water shortages are motivating discussions about wastewater recycling, which in turn affects the recycling of P in the system (Tangsubkul et al., 2005). Through this framing, P management synergies can be coupled to salient public health, provisioning, and resource allocation goals.

3.2. Linking factors

These eight categories are a guide to identify the types of factors that drive urban P dynamics. Our investigation revealed that it is also essential to consider relationships among factors both within and across categories. For example, a legacy of high access to financial capital in Linkoping, Sweden has led to the development of a highly centralized sewage system that makes it difficult to create plans to alter the system to increase nutrient recycling, because of the existing infrastructural inertia (Neset et al., 2008). This demonstrates the interconnectivity of factors across multiple categories and the importance of looking at cross-scalar effects (i.e., temporal effects through historical legacy of market and capital availability, current infrastructure, and future priorities and plans). Using systems thinking to determine how these factors are related to one another allows examination of causal relations, feedbacks, time lags, and networks of actors. There are multiple methods to determine the specific attributes of a system, and some are better suited than others depending on the system of factors one wants to consider (e.g., system dynamics, soft systems methods, or influence matrices (Iwaniec et al., 2014; Luke and Stamatakis, 2012)).

4.   Using the framework

Our framework is designed to flexibly help researchers ensure they have considered the broad suite of factors that influence urban P flows and their interactions, while leaving room for adaptation to city-specific factors. A well-rounded and thorough list of factors can be identified through interviews, literature review, expert deliberation, review of city documents, or any other means accessible to the researcher. We recommend the following broad steps to best utilize this framework in a city of interest:

- *Identify factors:* Systematically examine each P flow and use the eight categories in the framework to comprehensively identify the factors that affect, drive, or regulate each P flow. Although a full analysis of the system and the P SFA are necessary to identify all factors, it can be beneficial to start with P flows in smaller bounded subsystems (c.f. Table 1 column 3).

- *Identify relationships:* Organize the identified factors into causal chains (sequence of factors that cause the next) in order to reveal inter-linkages and feedbacks among factors (Meadows and Wright, 2008). Identifying connections among factors is essential in order to avoid unintended negative consequences of a management decision, and to identify potential positive synergies. Some factors may affect many different P flows in a city, and thus may be strategic points to improve P management. These key factors can often be identified by focusing on relationships and causal chains. For example, changes in dietary preferences through shifts in knowledge, culture, or economics, affect both P imported as food and P leaving the system through wastewater. This step can also be used to identify synergies between P management and other municipal management priorities. For example, concerns about water availability can be used as an entry point for wastewater recycling and thus P recovery.

- *Iteratively revise factors and relationships:* In many cases researchers will not have all the information to identify all relevant factors and relationships between factors that affect P cycling. Even when a factor is identified, the researchers may not have enough information on the nature of its relationship with P (e.g., positive or negative feedback) to know how changing the factor would affect P cycling. This may require engagement with decision-makers and other stakeholders, primary data collection, or literature review to fully understand the system of factors relevant to local P cycling. By collecting relevant new information on one factor, researchers may discover new linkages or other factors that are important in the system.

   Throughout the analysis, researchers should pay particular attention to factors with relationships to the "Future Priorities and Plans" category and key actors related to that category (thus the "Governance and Actors" category as well). This will ensure that the identified factors are relevant to stakeholders, which will facilitate engagement with stakeholders to collect missing information and will facilitate subsequent prioritization and trade-off analyses among the factors in order to implement changes to P management. As such, we note that the proposed steps are not necessarily sequential and may be conducted simultaneously or iteratively, thus incorporating new knowledge as it emerges.

5. Example of mapping the framework to Phoenix

Here we demonstrate the utility of this framework by mapping it on the results of an analysis of the food and agriculture subsystem in the Phoenix Metropolitan area (per Metson et al., 2012b). By explicitly considering factors that affected P cycling and the relationships among these factors, the authors of the study were able to better understand the system affecting local P cycling and identify possible interventions that took advantage of the relationships among factors. Here we show which categories or factors are represented in the study (in parentheses and italics), and discuss how considering causal chains of factors and explicitly examining multiple temporal and spatial scales helped contextualize P flows on the urban landscape.

P recycling at the urban-agricultural interface in Phoenix is high, but not because of direct concerns about P recycling or management. In fact, the desert climate and local soil type (*Biogeophysical situation*) do not favor P losses from the system, and as such, downstream pollution is not a large concern. However, water availability, international agricultural markets, and urbanization pressures were important concerns for farmers, businesses, and city managers (*Governance and actors*).

Concerns over water scarcity (*Future priorities and plans*) have translated into water recycling from sewage treatment plants to green space (*Infrastructure and land use*). This includes local agricultural production, where using reclaimed water on crops also recycles P in the reclaimed water. P in biosolids from the wastewater treatment plant, and local manure production from dairy farms, is recycled via application to local alfalfa fields. The P in alfalfa is then fed to local dairy cows, and a portion of the milk produced is consumed in Phoenix, also contributing to local P recycling. Cotton was the main agricultural crop in the region, but cotton prices dropped while the price of and international demand for milk increased (*Market and capital availability*). Dairy production has historically been present around many urban areas because of the perishability of dairy products. As the international price of milk increased (*Market and capital availability*), producers around Phoenix were able to meet more international demand by increasing herd size and switching less profitable acres of cotton to alfalfa to feed these [now more profitable] cows.

Current recycling of P at the Phoenix urban-agricultural interface is in many respects unintentional. If international market conditions or local water availability were to change, this serendipitous P recycling may decline. The authors could not have understood why recycling was so high, and how P may cycle in the future, without explicitly looking at the local "Biogeophysical Situation" and "Future Priorities and Plans" (i.e., limited water pollution risks but concern over water scarcity), local patterns of current and historical land use and infrastructure (i.e., proximity of cropping systems, dairy production, and residential areas, and wastewater recycling), and international market forces (i.e., changes in the prices of alfalfa, cotton, milk, and P fertilizers). Based on this system-level understanding, Metson et al. (2012b) suggested that water management, and perhaps future increases of P fertilizer prices, might be strategic ways to engage practitioners managing P (and coordinate their decisions) more intentionally. If P were to be managed intentionally in relation to crop production and waste management, it may be possible to maximize the benefits of efficient P use and local recycling.

6. Next steps

The framework developed here is a pragmatic step toward linking urban P SFAs to municipal priorities to better

understand how both planned and unintended changes may influence P cycling, but more detailed tools are required to facilitate the eventual implementation of solutions. A toolkit with a step by step guide and working quantitative models, where scientists and stakeholders can quantitatively explore the full suite of available management priorities, and their effect on other urban priorities would complement the framework presented in this article. In addition to more quantitatively understanding the impact of combinatory sets of management priories, and explicitly taking into consideration the effect of driving factors through causal links and feedbacks, it will be necessary to evaluate management options for their *desirability*. Different world visions, understanding of problems, as well as limited social and economic capital can all lead to disagreements on how to allocate resources and manage the city (Wiek and Binder, 2005). A multi-criteria approach to prioritizing the saliency of the factors will be necessary to explore and negotiate potential intervention points. For example, one could prioritize interventions based on urban P dynamics (size of the stocks and flows), system structure (number of relationships and network centrality) and normative features (desirability and sustainability). Our framework, Cordell et al. (2011)'s decision-making framework, and the more quantitative toolkit proposed above could be combined to facilitate the co-creation of knowledge and future visions of desired and sustainable P cycling with stakeholders. Engagement should be viewed as a continuation of the iterative process that the framework requires, where refinement in the understanding of driving factors and their dynamics, and P flows themselves is bound to happen with different types of knowledge interactions (Folke et al., 2005). Such co-creation has the potential to overcome barriers to the implementation of solutions, using the suite of tools available for the creation of legitimate and adapted strategies for change at the science-policy interface {Hezri, 2006 #1262}.

7.   Conclusion

Sustainable P management is a growing concern from both a global and local perspective. Increasing our understanding of urban P dynamics and its drivers is key to implementing changes in the management of P. Our framework allows researchers to build a broader system-level understanding of the context within which urban P stocks and flows occur by identifying the factors that drive P dynamics in a particular city. Understanding linkages among these factors can help identify causal relationships and feedbacks, and thus recognize system-level changes that might have positive effects on multiple aspects of urban sustainability, and avoid suggesting management options that may be detrimental to other locally or globally important sustainability priorities. The ultimate objective here is to increase the sustainability of P management and this requires scientists and practitioners to understand both the stocks and flows of P and the factors that affect their current and future management. Our framework constitutes an important step in achieving this objective by allowing researchers and urban stakeholders to find linkages between P cycling and existing priorities and plans, even where P is not currently a management priority,

and making it possible to identify synergies and trade-offs that may exist.

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