URBAN PHOSPHORUS SUSTAINABILITY: HOW HUMAN DIET, URBAN AGRICULTURE AND SOCIOECOLOGICAL CONTEXT INFLUENCE PHOSPHORUS CYCLING AND MANAGEMENT

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ABSTRACT

Sustainable phosphorus (P) management is emerging as a pressing concern at both global and local scales because P is an essential nutrient in agriculture and an important aquatic pollutant. While there has been considerable progress in our understanding of the problems caused by human alteration of the P cycle, there remain critical knowledge gaps that hinder our ability to effectively manage this key element. For example, although we know cities are hotspots of P movement on the landscape because they concentrate P inputs (food) and P outputs (food and sewage waste), we have limited knowledge about how P moves in and through cities and the role cities could play in more sustainable P management. We also do not know how important individual choices, such as diet, are in determining overall demand for P. In this thesis, I explore the role cities can play in improving P management, through diet and urban agriculture. Throughout, I focus on how an interdisciplinary approach that incorporates the ecological, social, and technological factors that drive urban P cycling can enhance our ability to answer questions about P management in cities.

I first focused on the role of human dietary choices in P demand through time examining how changes in diets have altered demand for P resources over the past 50 years. My results indicate that the global per capita P footprint (the per person amount of mineral P required to produce food crop or animal products for consumption) increased 38% between 1961 and 2007. There is considerable variability in per capita P footprint and in the rate of change in per capita P footprint among countries, mostly associated with differences in meat consumption. In one city in a high-P consuming country (Montreal, Canada), I used substance flow analysis to quantify the P cycle in the food system and in the urban agriculture system of the city. I determined that most of the P entering Montreal accumulates in landfills and little is recycled. The majority of inputs applied to urban agriculture are from recycled sources (such as compost), hinting that, although urban agriculture is a quantitatively small component of the city's P cycle, it could be a catalyst towards more recycling. To assess this potential, I needed to understand not only the P cycle itself, but also the social, ecological, and technological driving factors of urban P cycling. To develop a complete set of social, ecological and technological drivers I might examine in Montreal, I conducted a comprehensive literature review of the drivers in urban P substance flow analyses from around the world. Using a systems thinking lens, I found eight categories of driving factors that should be included in an interdisciplinary analysis of urban P cycling. Including these categories of driving factors will improve researchers' ability to identify synergies between P management solutions and problems and other urban priorities and plans. Finally, I return to the Montreal case study to examine these categories of driving factors in detail. I used semi-structured interviews with key stakeholders, participant observation, and document review to identify Montreal-specific driving factors that act as facilitators and barriers to increasing P recycling. I found that a law on the books that encourages organic matter recycling, and strong support for increasing the presence of urban agriculture in Montreal have the potential to facilitate P recycling. In order to take advantage of these facilitators however, it will be necessary to overcome the barriers associated with cultural inertia, lack of knowledge, and lack of proper infrastructure. Increasing social capital, as well as connecting urban agriculture and waste management objectives, and increasing knowledge about composting can help overcome these barriers.

Overall, my thesis indicates that considering both the broader system of social, ecological, and technological factors that drive P cycling, along with understanding the quantitative flows of P, will improve our ability to manage P in ways that are that are locally relevant. This work facilitates bridging the gap between theoretical understanding of P management problems and solutions and real-world change by quantifying and qualifying two understudied solutions (diet and urban agriculture), and integrating natural and social science methods to allow us to better understand the current and potential role of cities in P sustainability.

RÉSUMÉ

La gestion durable du phosphore (P) représente une préoccupation importante tant à l'échelle mondiale que locale, car le P est un nutriment essentiel en agriculture et un important polluant aquatique. Bien qu'il y ait eu des progrès considérables dans notre compréhension des problèmes dans le cycle du P, liés à l'activité humaine, il reste encore d'importantes lacunes de connaissances qui doivent être comblées afin d'augmenter notre capacité à gérer efficacement cet élément clé. Par exemple, même si nous savons que les villes sont d'importants systèmes dans le mouvement du P, puisque s'y concentrent les flux entrants de P (la nourriture) et les flux sortants

(déchets alimentaires et eaux usées), les connaissances sur la façon dont se déplace le P à l'intérieur et à travers les villes et le rôle que ces dernières peuvent jouer dans la gestion durable du P nous font défaut. L'importance des choix individuels, tels que les choix alimentaires dans la demande mondiale pour le P, reste incomprise. Dans la présente thèse, j'explore le rôle que les villes peuvent jouer dans l'amélioration de la gestion du P, particulièrement à travers les choix alimentaires et la pratique de l'agriculture urbaine. Je me penche sur la façon dont une approche interdisciplinaire intégrant les facteurs écologiques, sociaux et technologiques qui influencent les flux et la gestion du P urbain.

Dans mon premier chapitre de recherche, je me concentre sur le rôle des choix alimentaires humains dans la demande du P à travers le temps. J'examine de quelle façon les changements dans les régimes alimentaires ont modifié la demande de ressources de P au cours des 50 dernières années. Mes résultats indiquent que l'empreinte de P par habitant mondial (montant de P minéral nécessaire par personne pour la production alimentaire animale ou végétale qu'elle consomme) a augmenté de 38% de 1961 à 2007. Il existe une variabilité considérable dans l'empreinte de P par habitant et le taux de changement de l'empreinte par habitant entre les pays qui sont surtout associés à des différences dans la consommation de viande. Par la suite, j'examine une ville d'un pays avec une grande empreinte de P selon les choix alimentaires des citoyens (Montréal, Canada). J'ai utilisé la méthode d'analyse des flux de matière afin de quantifier le cycle du P dans le système alimentaire et dans le système de l'agriculture urbaine de la ville. J'ai déterminé que la plus grande partie du P entrant à Montréal s'accumule dans les sites d'enfouissement et que peu de P est en fait recyclé. En revanche, la majorité du P appliqué en agriculture urbaine provient de sources recyclées (comme le compost), laissant entendre que bien que l'agriculture urbaine représente une petite composante quantitative du cycle du P de la ville, le P pourrait être un catalyseur vers plus de recyclage. Pour évaluer ce potentiel, j'avais besoin de comprendre non seulement le cycle du P lui-même, mais aussi les facteurs sociaux, écologiques et technologiques qui influencent le cycle du P urbain. Pour développer un ensemble complet de facteurs sociaux, écologiques et technologiques qui pouvaient être examinés à Montréal, j'ai effectué une revue de la littérature exhaustive des études d'analyses de flux du P urbain. En utilisant la pensée systémique, j'ai trouvé huit catégories de facteurs qui devraient être inclus dans une analyse interdisciplinaire du cycle urbain du P. L'inclusion de ces catégories de facteurs d’influence permet d'améliorer la capacité des chercheurs à trouver des synergies entre les solutions possibles pour la gestion du P, et d'autres priorités et plans pour une ville. Dans le dernier chapitre de recherche de la présente thèse, je reviens à l'étude de cas de Montréal, pour examiner les facteurs qui influencent la gestion du P en détail. J'ai mené des entretiens semi-structurés avec des intervenants clés, une observation participante et une revue de documents pour identifier les facteurs d’influence spécifiques à Montréal qui agissent comme facilitateurs ou comme obstacles à l’augmentation du recyclage du P. Mes recherches suggère qu’une loi sur le recyclage de la matière organique et qu’un appui citoyen pour accroître la présence de l'agriculture urbaine à Montréal auraient le potentiel de faciliter le recyclage du P. Cependant, pour profiter de ces facilitateurs, il sera nécessaire de surmonter les obstacles liés à l'inertie culturelle, de même qu’au manque de connaissances et à l’absence d'infrastructures adéquates pour le compostage. Le fait d’augmenter le capital social afin de connecter les objectifs d’agriculture urbaine et de gestion des déchets et d’augmenter le niveau de connaissances sur le compostage pourraient aider à surmonter ces obstacles.

Dans l'ensemble, ma thèse indique qu’il est important de tenir compte à la fois du système de facteurs sociaux, écologiques et technologiques qui influencent le cycle du P et des flux quantitatifs du P. Mes résultats suggèrent que de tenir compte de ces aspects permettra d'améliorer notre capacité à gérer le P de façon plus durable, par des moyens adapter au contexte local. Ce travail contribue à combler l’écart qui existe entre notre compréhension théorique des problèmes et des solutions liés à la gestion du P et des changements réels dans les pratiques de la gestion de cet élément, en quantifiant et en qualifiant deux solutions peu étudiées : les choix alimentaires et l'agriculture urbaine. L’intégration de méthodes des sciences naturelles et sociales nous permet de mieux comprendre le rôle présent et potentiel des villes dans la gestion durable du P.

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PREFACE & CONTRIBUTION OF AUTHORS

The following thesis is manuscript-based and in accordance with McGill University guidelines. The thesis is made up of four main research articles, in addition to an introduction and a conclusion chapter that present the broader context and relevance of the thesis work as a whole. Note that references follow the *Ecology* journal style. I am the lead author on all chapters, as I led the development of research questions, lead or carried out all data collection, compilation and analysis (including statistics), and lead the preparation of all manuscript texts.
Co-authors for the four main research articles made the following contributions:

Chapter 2 has been published

Geneviève S. Metson, Elena Bennett, James Elser. (2012). The role of diet in phosphorus demand. Environmental Research Letters, 7 044043 doi:10.1088/1748-9326/7/4/044043.

-Elena Bennett and James Elser contributed to the initial idea of looking at the effect of dietary changes on phosphorus resource consumption. Elena Bennett provided guidance on methods, as well as focusing the scope of the paper, and both Elena Bennett and James Elser provided feedback on the manuscript.

Chapter 3 is under review for publication

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-Elena Bennett provided guidance on the preparation of the research design and feedback on the manuscript.

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-All co-authors contributed to the development of ideas for the need for the framework and the framework itself and subsequently provided feedback on the manuscript. David Iwaniec assisted G. Metson with data collection (literature review) and the preparation of the manuscript.

Chapter 5 has been submitted for publication

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1 INTRODUCTION

1.1 The global phosphorus (P) challenge and its potential solutions

People have significantly altered the P biogeochemical cycle, changing P flows between ecosystems (Smil 2000), modifying the geographic distribution of P stocks around the world (MacDonald et al. 2011), and greatly accelerating the global P cycle (Bennett et al. 2001). Global P cycling naturally happens on geological time scales, where P is eroded from rocks, tightly recycled through ecosystems, eventually ending up in the ocean where it is reincorporated into sediments (Filippelli 2008). People have accelerated the extraction process through mining to produce P fertilizer for agricultural systems (Tilman et al. 2002), roughly tripling the mobilization of P at the global scale (Smil 2000). Although fertilizer use has markedly improved crop productivity, it has led to increased losses of P to waterways from agricultural landscapes that in turn threaten important aquatic resources with overfertilization (Carpenter et al. 1998a).

Anthropogenic changes to the P cycle pose a two-sided problem. On the one hand, we face scarcity of non-renewable mined-P resources (Cordell and White 2011, Viccari 2011), with a limited amount of concentrated P deposits (Cordell 2010) geopolitically concentrated in a few countries (Cooper et al. 2011). Three countries (Morocco, China, and the USA) control 93% of the currently known mineable resource (Van Kauwenbergh 2010, Jasinski 2011). Because there are no known substitutes for P in agriculture, the high levels of current P extraction create concern for future food security. On the other hand, P losses from agricultural and urban ecosystems to aquatic ones through runoff and erosion have led to eutrophication in many lakes and coastal ecosystems (Carpenter et al. 1998b, Smith and Schindler 2009). The number of hypoxic water bodies around the world have been increasing, threatening ecosystem health, water quality (affecting drinking water supply as well as recreation) and fisheries on which we depend (Diaz 2001). Current management of P resources is thus both a threat to future food security and to the downstream ecosystems on which we depend for a multitude of ecosystem services. Solutions to both problems are related —the less P is wasted or lost to downstream ecosystems, the more P is available for use elsewhere and in the future.

A broad range of technological and system management solutions exist to better manage P throughout the food system (Cordell and White 2013). Only a very small fraction of P we mine is ultimately consumed by humans, in fact only around a fifth of the P mined for fertilizer production is consumed by humans, which leaves ample room for improving how we manage P (Cordell et al. 2009a, Schroder et al. 2010). In addition to losses before consumption, there is also potential to recycle post-consumption P before it is lost to waterways and landfills, since approximately 98% of P consumed by people is excreted (Drangert 1998). Most solutions aim broadly to decrease the demand for P (especially mined P) and decrease unwanted P losses by increasing efficiency of P use or by increasing recycling of P. Efficiency can be increased by choosing or engineering more efficient P-use crops and animals, implementing best management practices for fertilizer applications, decreasing crop and food losses and waste (from fields, processing, and home consumption,), and by altering human and animal diets (Cordell and White 2013). Recycling can be increased through the reuse of crop and food waste, animal manures, and human excreta (Cordell and White 2013). Solutions to increase P use efficiency and recycling may include laws and policies, behavioral and cultural shifts, and changes in infrastructure, technologies, and organization (e.g., proximity of P sources and uses) throughout the food system. Cordell et al. (2009b) demonstrate through global scenario work that there is no magic bullet solution; rather, the changes mentioned above must be used together in various combinations to ensure a long-term, affordable, and equitable supply of P to agriculture, while minimizing pollution to meet future increases in world population and their associated demand for food and production of waste.

Although the hypothetical impact of the large-scale implementation of solutions has been estimated, and very locally-specific examples of implementation of solutions exist, there is still a considerable need for further research to be able to determine the real-world scalability of solutions. For example, globally, cities currently have the potential to recycle almost 0.88 million tons of P from urine and excreta and that amount may double or even quadruple by 2050 due to increases in population, urbanization, economic growth, and sewage infrastructure modernization (Van Drecht et al. 2009, Mihelcic et al. 2011). Specific solutions for any one city or region may vary. Through a series of case studies, Cordell et al. (2011) show that centralized (e.g., struvite (magnesium ammonium phosphate) recovery at a wastewater treatment plant in Canada) and decentralized (e.g., urine diverting toilets in Sweden) have been implemented to recover P from waste streams. We still require more information to understand the factors that may impact the feasibility and desirability of solutions in different locations, as well as how such solutions may be implemented within the context of other sustainability priorities and plans (Neset and Cordell 2012, Cordell and White 2013). Solutions should be tailored to specific places in a way that takes into account context at appropriate temporal, socio-political, and spatial scales because the biophysical and social contexts of a location or group of actors will affect the relevance and effectiveness of solutions (Metson et al. 2013).

1.2 The role of food consumption and cities in P cycling

Peoples' dietary choices are a key driver of P use, and thus a key leverage point to decrease P consumption globally (e.g., Cordell et al. (2009b) and Cordell and White (2013)). Human diet is a driver of anthropogenic demand for agricultural resources because different crops and animals require different amounts of nutrients, water, land, and energy (Pimentel and Pimentel 2003, Reijnders and Soret 2003, Kastner et al. 2012). Although food consumption decisions may be made on an individual scale, factors such as physical and economic access to different food stuffs, as well as cultural preferences, influence individual and group behavior (Furst et al. 1996, Drewnowski and Popkin 1997, Delgado 2003). Because these factors vary widely around the world, the contribution of individuals, cities, and nations to P demand through dietary choices, and possible solutions to high mined-P demand vary across the planet.

Understanding urban P cycling is a key component in understanding anthropogenic P cycling at regional and global scales (Grimm et al. 2008). Cities drive the production of high P-products through consumption (including human and pet foods, landscaping and gardening materials, timber products, and construction materials), and produce high-P waste (human excreta, and food and landscaping waste). As such, cities are linked to agricultural and other ecosystems through trade, as well as through hydrological and atmospheric dispersion patterns. Such linkages make cities part of problematic P management, but also key to finding solutions. In fact, cities are often centers of creativity and innovation, and as such altering natural resource management within cities can have large effects at broader geographical and political scales (Florida 2003). Developing a conceptual and empirical understanding of urban P cycling is thus a key part of understanding global P cycling (as cities are key in other types of global change and resource management) and finding solutions to problematic P management locally and globally.

In addition to their relevance globally, cities are important as they are characterized by the unique biogeochemistry of a highly complex socio-ecological system (Lin et al. 2014). In urban ecosystems, the flow of P through the city is controlled by people and by human interactions with ecosystems. Individual and group decisions about food and other imports, land use, diet, and waste management all affect how P moves in, within, and out of cities (Chowdhury et al. (2014), Figure 1.1). And these flows, whether managed or unmanaged, are in turn affected by the biophysical environment of the city. For example, precipitation and temperature affects landscaping and agriculture choices, which may affect urban P cycling by increasing or decreasing use of fertilizers or amount of runoff (e.g., Metson et al. (2012a), Metson et al. (2012b)). In order to understand P cycling in cities it is thus important to take into consideration both the social (including technological) and the ecological context that influence P flows in any one city.

Cities could be keystones in a more sustainable anthropogenic P cycle as they are unique in their ability to link concentrated P demand (food and other goods) and P pollution (high production of food, organic, and sewage wastes) on the landscape. Currently, P pollution and scarcity are often handled separately because they appear to be opposite issues and one or the other typically dominates in a particular location or at a particular time. This conceptual separation of pollution and scarcity is a lost opportunity in that areas that face pollution may be excellent sources of P for other regions that suffer from scarcity (MacDonald et al. 2011). Cities are vulnerable to P scarcity through food pricing and availability, as well as to pollution because of poor urban waste management. Because cities face both scarcity and pollution, they have an important role in solving both problems simultaneously, recycling P that flows through cities as food and waste back into local agriculture, including urban agriculture (UA). In addition, because of their purchasing power and capacity to treat large amounts of waste, changes towards more recycling and efficient P management within the city may act as a catalyst towards more sustainable P management at broader scales.

Urban agriculture has the potential to play a particularly important role in addressing both scarcity and pollution concerns within cities. UA, defined as food production (crops and animals) within the metropolitan boundaries, like all agriculture, requires P inputs to ensure production. The location of UA within the city should mean that UA practitioners have relatively easy access to P inputs in the form of organic matter from food, yard, and sewage waste (if properly treated). These P sources are often difficult to recycle over long distances because organic matter has a high water content (as mentioned in Baker (2011)). UA thus has a unique advantage for recycling urban P waste back into food production because of its proximity. In addition, because of the proximity of UA production to consumers, food waste can be decreased (by reducing spoilage during transit), thus further increasing the efficiency of P use through the food chain. By increasing P use efficiency and increasing P recycling, UA can decrease dependence on mined P for food production, and decrease pollution, thus providing an important addition to P sustainability.

Despite its potential importance in P management, and its ability to provide multiple social and ecological benefits, UA remains understudied with regards to nutrient cycling. In Europe, UA has been shown to provide urban food system resilience in times of war and economic depression by providing an alternative source of fresh food to citizens (Barthel et al. 2013). In Australia, UA has been a part of sustainable urban water management (Moglia 2014). Increased food security (Altieri et al. 1999), greater community engagement and social cohesiveness (Saldivar-Tanaka and Krasny 2004), provision of urban green space that promotes biodiversity and pollinators (Goddard et al. 2010), and serving as an educational space for people to learn about ecosystem services and food production are all cited as benefits of UA around the world (Lovell 2010, Hodgson et al. 2011, Duchemin 2013). However, although it is often mentioned as a potential benefit of UA, few studies have explicitly and empirically evaluated the role of urban and peri-urban agriculture in using and recycling nutrients. One notable exception is work conducted by the International Water Management Institute in West Africa, especially in the cities of Accra, Kumasi, and Tamale in Ghana (Drechsel et al. 2007). Here, studies have focused on how nutrient and water recycling through urban and peri-urban agriculture can assist in both food security and sanitation concerns (e.g., Drechsel and Kunze (2001), Leitzinger (2001), Drechsel et al. (2004), Danso et al. (2006), Drechsel et al. (2010), Van Rooijen et al. (2010)). However, to my knowledge, this is the only quantitative work explicitly considering the potential for UA to contribute to more sustainable nutrient management. As part of the complex and heterogeneous urban fabric, the specific role of, benefits from, and challenges associated with UA may vary for different cities (Hodgson et al. 2011) and so may its role in P cycling. As such, more studies are needed to understand UA's real potential (both quantitatively in terms of recycling, but also qualitatively as a way to change citizens relationship to the food system and the environment outside of the urban realm (Thibert 2012)) as a solution to the P management challenges communities face locally across different social, ecological and technological contexts.

1.3 Knowledge gaps to move from problems to solutions

Phosphorus management is a pressing problem (Childers et al. 2011, Elser and Bennett 2011), but real-world changes in P management have yet to comprehensively address the problem (Wyant et al. 2013, Scholz et al. 2014). For example, although we understand many of the causes of Lake Erie's seasonal eutrophication, trends in these causes indicate increases in algal blooms in the lake if important management changes are not implemented (Michalak et al. 2013). Similarly, although we know that the geopolitically concentrated nature of mined P resources may cause increased P fertilizer prices and threaten food security, we have yet to develop large scale or coordinated alternative sources of P through recovery and reuse (Cordell et al. 2011). The causes and implications of unsustainable P management operate at multiple interacting scales and involve both social and ecological factors with notable local variability (Rockstrom et al. 2009, Carpenter and Bennett 2011, Syers et al. 2011), making P management a complex problem (Metson et al. 2013), in which real-world change is difficult.

Decision-making to improve P management is complex. Solving global environmental change problems such as P management can be difficult because solutions depend on local management, as well as on emerging properties at broader spatial, temporal, and political scales that can feedback to affect local management (Wilbanks and Kates 1999). A cross- or multi-scale approach is thus called for when addressing global environmental challenges to ensure a better comprehension of the situation(s) at hand and manage resources in a way that minimizes negative trade-offs (Wilbanks and Kates 1999, Zermoglio et al. 2005). Coordinating the efforts of multiple actors at multiple scales, while also taking into consideration local context and other sustainability priorities (e.g., water, energy) is necessary but no small feat for sustainable P management (Metson et al. 2013, Cordell and Neset 2014).

However, thus far, most scientists have addressed P either as a global problem (e.g., Van Kauwenbergh (2010), Van Vuuren et al. (2010), Vaccari and Strigul (2011)) with no or little local context, or as a local problem (e.g. eutrophication of a lake in one region (e.g., Wu et al. (2012)), or P cycling within one country (e.g., Matsubae-Yokoyama et al. (2009)) with limited discussion of the global context. Although theoretical work has proposed ways to begin to integrate some of the multi-scalar elements of P management from a policy perspective (e.g., Cordell and Neset (2014)), and we widely acknowledge the need for a multi-scalar perspective (Wyant et al. 2013, Scholz et al. 2014), few studies integrate multiple scales in empirical work.

In addition to multi-scale considerations, P studies and management would benefit from an interdisciplinary approach that incorporates social and ecological understanding of the issues. Sustainability challenges and complex problems call for an interdisciplinary, and even transdiciplinary approach (Kates et al. 2001). Furthermore, science concerned with complex policy-relevant phenomena with high uncertainty requires us to move away from traditional disciplinary separation towards more iterative and flexible problem-focused (Funtowicz and Ravetz 1993) and solution-oriented (Sarewitz et al. 2010) methodologies that draw upon multiple disciplines and actors. In fact, the research paradigm around natural resource management problems has shifted from "knowledge then action" to an increasingly continuous and iterative process of knowledge production and management shifts (combining many disciplines and practitioners, Berkes et al. (2000)). Despite the clear need, it however remains challenging to deeply integrate social and ecological components of environmental problems and solutions because of different conceptualizations of research questions, methods, and even definitions of key terms and concepts between the natural and social sciences (e.g., scale: Gibson et al. (2000), or water management: Kemp-Benedict et al. (2010)).

P sustainability exhibits the complex characteristics of a problem that would benefit from an inter- or trans-disciplinary approach (Wyant et al. 2013, Scholz et al. 2014), especially when studying the dynamic socio-ecological nature of cities (Grimm et al. 2000, Collins et al. 2010). However, thus far, most P cycling work has focused either on the natural or physical science aspects of P cycling (where and how much P moves and is stored, e.g., MacDonald et al. (2011), Sattari et al. (2012)) or on the social science aspects (why P moves and is stored, e.g., Weikard and Seyhan (2008)), but few studies have attempted to examine both or their interactions.

In this thesis I aim to contribute to filling these knowledge gaps, focusing on the role of human diet choices and that of cities in ensuring more sustainable P management. I explicitly consider the importance of multiple scales of the P problem (global, national, and local (city and sub-city scale)), focus on the importance of local driving factors in cities, and integrate both social and physical science methods to gain a fuller understanding of P management problems and solutions and cities as complex socio-ecological systems.

1.4 Thesis goals to fill knowledge gaps

Cities are hotspots for P cycling, and are decision-making centers that influence environmental change and management at broader scales (Grimm et al. 2008, Ernstson et al. 2010, Elmqvist et al. 2013). Cities also concentrate people and their consumption habits, dietary choices, and waste management practices as well as their preferences for and understanding of our agricultural and food systems (thus having the potential to influence trade, fertilizer and food and sewage waste management for example). As such, cities have the potential to impact P management far beyond their borders. Furthering our understanding of urban P cycling and its drivers can broadly improve P management (Figure 1.1). In this thesis, I contribute to knowledge about:

- How dietary choices have influenced P demand through time,
- How P cycles within cities through a case study from Montreal,
- The role of urban agriculture in P cycling using the same case study, and
- The importance of social, ecological, and technological driving factors in urban P cycling and in solutions to improve the sustainability of P cycling (both generally and in the Montreal case study, Figure 1.1).

In Chapter 2, I examine how national dietary changes have altered demand for mined-P resources over the past 46 years. This chapter focuses on the global quantitative aspects of P cycling but takes a cross-scalar and interdisciplinary approach by examining the P footprint of various dietary choices, linking per capita national dietary choices to agricultural practices and P mining at the global scale. I found that countries' increased preference for meat is a large part of what is driving increasing demand for mined P, and that high meat diets were correlated with wealth. As such, I recognized the importance of people and their choices, and thus continue to focus the rest of the thesis on where large concentrations of people live: cities, and using a case study city in a country with a high P footprint.

In Chapter 3, I measure P flows in a city of a developed country (Montreal, Canada). Montreal is a relatively high P consumer, in part because of dietary choices, with the potential to play an important role in decreasing P demand. I use substance flow analysis to quantify P flows in the food system of the city. I also collect the first existing data on P cycling in the urban agriculture (UA) system of a city in a developed country. My results indicate that P recycling is currently low in Montreal (6% of P in food and yard waste), and that more recycling might be possible through UA and peri-urban agriculture. The study also showed that we need a better understanding of the social, ecological, and technological drivers of urban P cycling and its management to improve the relevance and adoption of management solutions.

Having determined that social and ecological drivers are critical to understanding and improving, P management in Chapter 4, I use a comprehensive literature review to determine the role these factors play in driving urban P cycling in cities around the world. I review urban P substance flow analyses in 18 cities, focusing on gaps in the knowledge required to implement P management solutions. This review yielded a framework to more systemically include driving factors in urban P work; however, it also strongly suggests that the heterogeneity of cities requires researchers to determine site-specific driving factors and solutions for each city.

In Chapter 5, I thus return to the Montreal case study to build upon the quantitative information gathered in Chapter 3 and use insights from Chapter 4 to explore the facilitators and barriers to increasing P recycling in the city. In this last chapter I use social science methods to complement the physical science methods used in Chapter 3. Together these four chapters contribute to a better understanding of P cycling, and how we may take advantage of site-specific synergies with other plans and priorities to decrease mined P demand and increase P recycling.

1.5 Figure

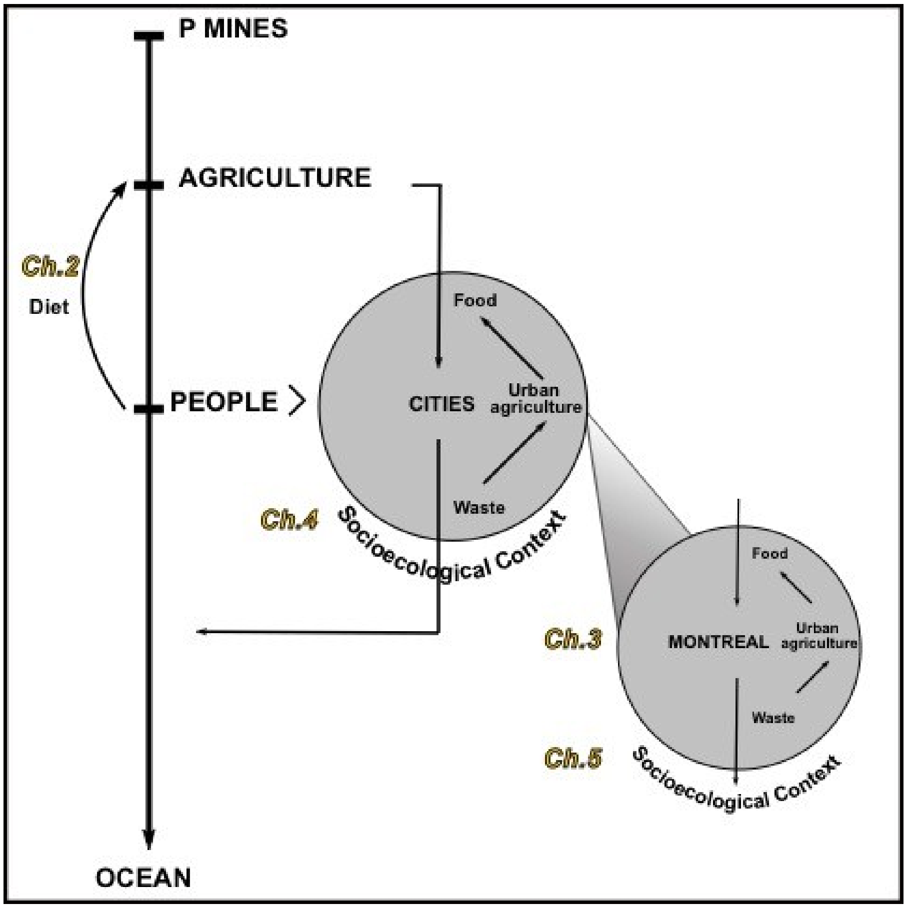

Figure 1.1 Conceptual framework of this thesis contributions to knowledge of anthropogenic P cycling. Current human P use has resulted in a one-way flow from P mining to accumulation in the oceans. Two key elements along this path are agriculture because it uses P fertilizer and produces food, and people as they drive food demand and produce high P waste. Cities are concentrations of people and as such concentrate the demand for P in food and the production of high P waste, but also have the capacity to recycle P through urban agriculture. In the thesis I focus on the role of cities in P cycling, looking at the role of human diet more globally (Ch.2), the importance of socioecological context (Ch.4) and use Montreal as a case study (looking at quantitative flows Ch.3, and context Ch. 5).

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2 THE ROLE OF DIET IN PHOSPHORUS DEMAND

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2.1 Abstract

Over the past 50 years, there have been major changes in human diets, including a global average increase in meat consumption and total calorie intake. We quantified how changes in annual per capita national average diets affected requirements for mined P between 1961 and 2007, starting with the per capita availability of a food crop or animal product and then determining the P needed to grow the product. The global per capita P footprint increased 38% over the 46 year time period, but there was considerable variability among countries. Phosphorus footprints varied between 0.35 kg P $capita^{-1}$ yr^{-1}(DPR Congo, 2007) and 7.64 kg P $capita^{-1}$ yr^{-1} (Luxembourg, 2007). Temporal trends also differed among countries; for example, while China's P footprint increased almost 400% between 1961 and 2007, the footprints of other countries, such as Canada, decreased. Meat consumption was the most important factor affecting P footprints; it accounted for 72% of the global average P footprint. Our results show that dietary shifts are an important component of the human amplification of the global P cycle. These dietary trends present an important challenge for sustainable P management.

2.2 Introduction

Phosphorus (P) is an essential element for all life (Smil 2000) that is often limiting to primary production across a diverse range of ecosystems (Elser et al. 2007). Thus, its addition to soil is a key part of high-yield agriculture (Tilman et al. 2001, Tilman et al. 2002). Anthropogenic changes to global P cycling, largely due to mining P for use as fertilizer, have increased the rate of P movement from mineral deposits to the ocean four-fold (Smil 2000, Childers et al. 2011). Such increases are principally due to three changes in the global food system: increases in population, which require an overall increase in food production (Cordell et al. 2009a); changes in diet to more P-intensive products (Keyzer et al. 2005); and changes in agricultural methods, including intensification of fertilizer inputs to increase yields (Tilman et al. 2002, Godfray et al. 2010).

These anthropogenic changes to the P cycle present an interesting paradox. On the one hand, we face rising prices and potential scarcity of non-renewable P resources (Cooper et al. 2011, Cordell and White 2011, Vaccari and Strigul 2011). The finite supply of P is a key concern because there are no substitutes for P and we cannot produce more than exists on Earth. On the other hand, excessive P losses to aquatic ecosystems through runoff and erosion have caused the eutrophication of many lakes and coastal ecosystems (Carpenter et al. 1998, Bennett et al. 2001, MacDonald and Bennett 2009, Smith and Schindler 2009, MacDonald et al. 2011). The overuse of P resources is both a threat to food security and to downstream ecosystems.

To identify strategies that mitigate the losses of P that cause eutrophication and to extend the lifetime of existing P resources, researchers have examined increasing P use efficiency (Crews 2005, Gaxiola et al. 2011, Simpson et al. 2011) and increasing P recycling (Cordell et al. 2011, Mihelcic et al. 2011, Rittmann et al. 2011, Dawson and Hilton 2011) in the context of P sustainability. We lose the majority of P applied to crops along the agro-food chain and there is significant potential for improved practices at every step of the chain; from judicious fertilizer application, genetically modified crops, and vegetative buffers around streams, to recycling human urine and composting urban waste streams.

However, little previous work has quantified the role of diet in sustainable P management. We expect diet to play a key role because increased meat consumption amplifies the requirement for P fertilizer inputs (Pimentel and Pimentel 2003). The P required to produce meat is high because the process of converting feed to meat is inefficient, with P losses during feed production in addition to losses in excrement. If dietary composition (e.g., the fraction of meat in the diet) is associated with differences in P demand, then shifts in diet may drive important changes in the P cycle and diet modulation may be an important lever to help reduce P demand. Still, the importance of diet relative to other demand-side factors remains unclear. For example, Cordell et al. (2009a and b) suggest moving from a meat- to vegetarian-based diet as part of a sustainable P management plan. They estimated based on global generic vegetarian and meat diets (i.e. not specific to any one place or population) that if future populations ate a low P vegetarian diet, anthropogenic P consumption could be 50% lower in 2050 than in 2000, but they highlight the fact that there are few empirical data about the relationship between diet and P requirements nor comprehensive analyses of temporal dynamics or geographic variation.

While estimates of P requirements for generic meat versus vegetarian diets provide an important first step, such aggregated data offers little basis for individuals or political entities to consider diet mitigation as a strategy to reduce P demand. This is because regional diet patterns are unique (York and Gossard 2004) and meat consumption has changed unevenly across the globe, especially in concert with different patterns of shifting affluence (Grigg 1993). Such unevenness suggests that measures to reduce P demand via dietary shifts will also need to be location-specific. To address these issues, we examined diet changes between 1961 and 2007 and estimated their effect on P requirements to elucidate the relationship between diet and demand for P, to clarify how changes in diet might impact P demand, and to identify factors that may change the effectiveness of policies to reduce P demand by altering diet. We use the concept of a "dietary P footprint," defined as the amount of P required to produce a country's annual per capita food consumption, to answer the following questions:

1) How has the global food P footprint changed between 1961 and 2007, and do these changes differ in various countries around the world?
2) What are the primary drivers of differences in per capita food P footprints between countries?
3) How important are changing global diets, especially shifts in meat consumption, in explaining changes in total global P consumption?
4) What are possible future impacts of trends in P consumption?

2.3 Methods

2.3.1 P footprints

We quantified changes in P footprint – the average amount of mined P required to produce the food consumed per capita per annum – based on diet composition for a globally distributed set of countries between 1961 and 2007. We calculated P footprints for all countries for which data were available in 1961 (N=165) and 2007 (N=170). We also calculated the annual P footprints for 19 countries for each year between 1961 and 2007. These countries were chosen to represent: 1) all continents; 2) a wide range of changes in gross domestic product (GDP) over the study period; and 3) countries for which there were both food availability and GDP data from 1970 to 2007.

Using FAO Food Balance Sheets (2011) for each country, we took the per capita availability of nine crop categories (e.g., cereals) and five animal product categories (e.g., beef) and multiplied each by a conversion factor representing the amount of P needed to produce the product (Table 2.1 and 2.2, see SI material for more detail). We used crop categories rather than individual crops because some countries reported fertilizer application on crop categories while others reported individual crops. By using crop categories we could incorporate individual crops as well, thus creating a more representative global average. We used food availability as a proxy for food consumption (Jacobs and Sumner 2002), recognizing that standardized data for food consumption are not consistently available and that food availability has been successfully used as a proxy for dietary consumption by the FAO and other public agencies.

The conversion factors, used to determine the amount of mined P fertilizer needed to produce each crop or crop category, were calculated by multiplying the dry matter content of each crop category (Monfreda et al. 2008) and the average kg P present in the crop category (Monfreda et al. 2008, MacDonald et al. 2011) by the inverse of the phosphorus use efficiency (PUE, Table 2.1). PUE is an estimate of the recovery of P applied in the harvested crop. We calculated the global average PUE for each crop and crop category by dividing P in the harvested crop by the P applied to produce the crop, using fertilizer application data from approximately 80 countries (International Fertilizer Association (IFA) 2002). The fertilizer application rate used to calculate PUE of each crop category was weighted according to each countries' proportion of total production of each crop within each crop category (see SI material on methods for more detail). We assume the average PUE of crop categories to be constant through time to allow us to examine only the effect of only changes in diet and overall production without also considering changes in management.

To develop factors to convert animal products consumed to mined P needed to produce those products, we determined: the amount of feed necessary to produce each kilogram of each animal product; 2) the composition of this feed; and 3) the amount of P required to grow each feed crop (as per the method using PUE described above). These three steps are detailed below.

1. Calculating required feed quantities for animal production: To convert animal product availability to the amount of input feed, we used global average feed conversion efficiencies (kg of feed (dry mass) per kg of output (in carcass weight or weight of product for eggs and dairy)) for each animal product category (Bouwman et al. 2005, Mekonnen et al. 2012). To isolate the mined P required to produce meat and animal products, we considered only fertilized crops in the feed conversion efficiencies for each animal product. We used the feed conversion efficiency for mixed and landless production systems and multiplied this value by the proportion of animals produced in mixed and landless systems (Bouwman et al. 2005) and by the global average proportion of feed in the mixed and landless production systems made up of food crops, forage crops, and scavenging. We have excluded P inputs to animal production through pasture systems and by grass in mixed production systems in order to examine the impact on mined P alone.

2. Calculating feed composition and P contained in this feed: We converted the amount of feed consumed into the amount of P consumed by animals, recognizing that the amount of P in the feed is dependent on the composition of that feed. Feed can be divided into four diet composition categories: food crops, residue/forage crops, grass, and, food obtained by scavenging (Bouwman et al. 2005). Because we focused on the mined P requirements of diet we excluded grass. For each of the remaining composition categories, we calculated an average weighted P concentration. For food crops, P concentration was calculated by weighting the P concentration of food crops used for feed according to the global average production of each one of these crops (FAOSTAT Commodity Balance Sheets). For forage crops, we calculated the P concentration by averaging the P concentrations (USDA-NASS 2009) of all forage crops (Monfreda et al. 2008). For the scavenging category, we used the average P concentration for human-destined food crops.

3. Calculating P required for feed crop production: Finally, we converted the amount of P in feed to the P fertilizer required to grow these crops. We weighted the PUE of the three feed composition categories according to their proportion of the total feed required to produce each animal category. For the food crops category eaten by animals, we used PUE for the cereals crop category because they are the most widely used category of food crops diverted from food production as feed (the remaining food crops used are residues, Handy et al. 2005). We calculated the PUE of the residues/forage crop category using IFA (2002) forage crop P application rates, and used world average yields for cereal, oil crops, roots, and pulses to apply these fertilizer rates on (FAO, 2011), and an unweighted average of dry matter and P coefficients for crops categorized as forage (Monfreda et al. 2008). In order take into account the importance of by-products, i.e., scavenged crops, we used a neutral PUE value of 1. We thus used a PUE value of 1 for the proportion of animal categories produced with feed from scavenging. It is important to note that, although we take into consideration that grass and scavenged crops are not fertilized, these feed types remain important sources of P in the animal diet. By using feed conversion efficiencies that exclude the amount of grass required to produce the average kg of meat, or dairy and eggs, as we did, only mined P fertilizer is considered as an input to the food system (see SI material for alternative P conversion efficiencies based that include P inputs from pasture, SI Figure 2).

2.3.2 Explanatory factors and statistical analysis

To assess the role of diet relative to population growth in driving the demand for mineral P fertilizer, we preformed a simple time-line scenario comparison. To do this, we calculated overall annual global P demand between 1961 and 2007 by multiplying the annual global average per capita P footprint by annual population estimates (UN population division, 2011). We compared these data to P demand calculated using the same annual population estimates always using the global average per capita P demand from 1961, which eliminated the effect of changes in diet over time. This comparison isolates the role of diet relative to the role of population growth and other factors that influence P demand.

To assess the effects of development status on P use, we grouped countries into "developed" and "developing" categories based on their 2007 Human Development Index (HDI) value, placing countries with a score over 0.698 in the developed category, and those under 0.698 as developing (United Nations Development Programme 2011). We performed a Mann-Whitney U-test to compare the mean P footprint of developed and developing countries in 1961 and 2007. We also performed a paired Mann-Whiney U-test to compare developed and developing countries mean P footprint in 1961 to that of 2007 to determine whether there was a significant change in P footprint over time within each category.

We also examined potential drivers of differences in P footprints between countries to assess whether income and lifestyle choices played a role in determining P footprint of a country (Regmi 2001, Kearney 2010). To assess this hypothesis, we performed a linear regression analysis on the log transformed P footprints (2007) for all countries for which there were both P footprint and HDI data (128 countries). We also tested the relationship between HDI and P footprint for 18 countries for which both data were available annually from 1970 to 2007 using a generalized least squares model where HDI, country, and year were used as explanatory variables. We re-centered the data by dividing the annual P footprint value of a country by the average P footprint of that country from 1970 to 2007, and did the same transformation on HDI data. Re-centering the data around country averages allowed us to focus on the relationship between HDI and P footprint in the time-series data, and not the role of country per se. We also accounted for temporal auto-correlation by using a first-order correlation structure (CorAR1). All statistical analyses were performed in R (R Development Core Team 2011).

2.3.3 Future scenarios

To explore the impact of future diet choices on P demand, we used UN population projections (United Nations 2004) and FAO global dietary composition projections (FAO 2006) to model four future scenarios for the years 2030 and 2050, using 2007 as a base-line for comparison. The scenarios combine a future per capita diet from FAO with a low (12%), medium (35%), high (61%), and current trajectory (93%, i.e., current growth rate remains the same through out the time period) for population growth. We also calculated a future global average P footprint assuming a lacto-ovo vegetarian diet (contains no meat but includes eggs and dairy products) by converting future meat consumption to pulses (legumes such as lentils and beans) to create a fifth scenario with the lowest predicted population growth. To calculate the effect of increased or decreased meat consumption on demand for pulses, we used the ratio of protein content of meat to that of pulses and assumed a constant amount of protein in the diet. P requirements in all scenarios assume fixed 1961 to 2007 farming losses and efficiencies.

2.4 Results

Increases in population and in per capita food consumption combined to raise global P demand 198% between 1961 and 2007, from 5.9 to 17.6 Tg P (Figure 2.1). Assuming a constant 1961 diet through time while allowing only population to increase augments P requirements 115% from 5.9 to 12.7 Tg P. Shifts in diet thus accounted for almost 28% of the increase in demand for mined P since 1961. The global average per capita P footprint increased 38% between 1961 and 2007, from 1.9 to 2.6 kg P capita^{-1} year^{-1} (SI Table 1).

While there has been an overall increase in the global P footprint, there is considerable variation across countries (Figure 2.2, SI Figures 1 and 2, SI Tables 1 and 2). In 1961, the lowest P footprints were Rwanda with 0.45 kg P capita^{-1} year and the^{-}Maldives with 0.47 kg P capita^{-1} year$^{-1\ 1}$, and the highest were Argentina and Uruguay with 7.02 and 6.8 kg P capita^{-1} year^{-1}. In 2007, the lowest P footprints were the Democratic Republic of the Congo with 0.35 kg P capita^{-1} year^{-1} and 0.48 kg P capita^{-1} year^{-1} in Eretria, while the highest were Luxembourg at 7.64 kg P capita^{-1} year^{-1} followed by the United States at 6.89 kg P capita^{-1} year^{-1}. Countries in North America, Oceania, and parts of South America maintained the highest P footprints throughout the study period. Most of Europe, the ex-USSR, and South America had moderate P footprints (between 3 and 5 kg P capita^{-1} year^{-1}). The lowest P footprints throughout the study period were found in Asia and Africa (Figure 2.2).

Overall, the mean P footprint was significantly higher in developed than in developing countries in 1961 and 2007 (Table 2.3). The increase in P footprint between 1961 and 2007 was statistically significant for both developed and developing. Interestingly, two countries with the lowest P footprints in 1961 experienced the largest increases over the time period, a 507% increase in the Maldives and 417% in China.

Not all dietary choices have equal impact on P footprint values. Meat, egg, and dairy consumption account for the majority of an individual's P footprint (Figure 2.3). About 72% of the global average dietary P footprint between 1961 and 2007 was due to consumption of animal-based food groups. Beef is the most P intensive meat (SI Table 3). Overall, the contribution of vegetable-based food products to a country's P footprint is much smaller than that of meat and did not vary greatly among countries.

Human Development Index (HDI) and P footprints were positively correlated. In 2007, there was a positive linear relationship between the log of P footprint values and HDI (Figure 2.4). When considering selected countries over the full time period, the relationship between HDI and P footprint showed a similar relationship, and where a generalized least-squares model considering

HDI, country, and year was the best fit to the relationship between P footprint and HDI (Log-restricted-likelihood: 1028, AIC: -2010, SI Figure 4).

Based on expected changes in diet (i.e., increased meat and total calorie consumption) and future population projections, demand for P could increase by 68 to 141% by 2050 (that is, to between 27.1 and 39.1 Tg P from a 2007 value of 16.1 Tg P (not including fruits and vegetable consumption), Table 2.4). Per capita P footprint is predicted to increase from 2.45 in 2007 to 3.46 kg P $capita^{-1}year^{-1}$ in 2030 and to 3.67 kg P $capita^{-1}year^{-1}$ in 2050, a potential 50% increase in 43 years. However, if protein requirements were to be met by consumption of pulses instead of meat by 2050, the global average per capita P footprint would decrease by 20% compared to 2007 and the total global P use for food production would decrease 10% when such a diet is combined with the lowest population growth projections.

2.5 Discussion

Our results indicate that dietary choices, especially those related to meat consumption, have a large impact on the demand for P in food production. Approximately 28% of the total increase in P demand between 1961 and 2007 was due to changes in the global average diet, including increasing meat consumption.

As diets vary around the world, so do P footprints. Our analyses show that each country's P footprint changed uniquely through time, and that these changes were significantly correlated with wealth and development status. Citizens in poorer nations eat fewer calories and less meat and thus require less P to produce their diets. For example, China's ~400% increase in P footprint during the study period follows the country's rapid increase in wealth and changing life style. Nevertheless, China's per capita P requirements remain much lower than those for most of North America and Europe. The potential for dietary modifications to enhance global P sustainability will differ considerably from country to country and region to region depending on the role of diet in P demand.

Dietary changes have considerable potential to change the demand for mined P. In particular, reduced consumption of meat, and especially beef, could result in dramatic declines in P demand. Based on predictions of future diet and population, P requirements to feed humanity are expected to increase between 68 and 141% between 2007 and 2050. However, changes in diet and population will vary widely across the planet. Many developing countries will increase their nutritional and caloric intake, and thus their P footprint, in an effort to improve food and nutritional security. At the same time, our data indicate that developed countries have considerable scope to reduce their intake of P intensive food groups, particularly meat, a shift that would have both environmental and human health benefits (Uribarri and Calvo 2003). Measures for creating a more sustainable social and environmental food system will require different strategies in different places, and context should also be considered in evaluating diet and changes in diet (York and Gossard 2004).

Diet mitigation is only one strategy in a suite of options available to better manage the relationship between food systems and P cycling. For example, increasing PUE can reduce the amount of P required to produce each crop, and increasing recycling can reduce demand for newly mined P. In particular, increased recovery of P in manure and less P intensive methods of animal husbandry could enhance the P sustainability of the developing world's dietary transition towards a more meat and calorie intensive state (SI Figure 3). Sattari et al. (2012) estimate that if residual soil P was taken into account (which has accumulated between 1965 and 2007), the use of manure and mineral P fertilizer to meet crop requirements is between 1.68 and 2.08 x 10^{10} kg P, while estimates that do not include residual soil P are 50% higher. This is more than the amount of P required for our vegetarian and low population growth scenario without a change in PUE, indicating that both farm P management and diet mitigation will be important strategies in the future. However, PUE alone will not ensure long-term sustainability for P management. Diet modulation can reduce P demand throughout the food production and processing chain, and thus can be an important addition to P management shifts at the farm level.

Synergies between P sustainability and other sustainability priorities may be key to implementing change (Neset and Cordell 2012). Throughout the food and ecological footprint literature, increases in meat and processed food production are associated with increased environmental impairment. In particular, meat production produces more greenhouse gases and requires considerably more fossil fuels (Pimentel and Pimentel 2003, Reijnders and Soret 2003, Eshel and Martin 2006), water (Hoekstra and Chapagain 2007, Mekonnen and Hoekstra 2012), land (Kastner et al. 2012), and nitrogen (Bleken and Bakken 1997, Gerbens-Leenes and Nonhebel 2002) than similar levels of plant-based caloric and protein production. A less P intensive diet could thus also help address other sustainability challenges, and conversely, motivations to change diets for a variety of site-specific environmental reasons may help address P sustainability goals.

Our calculated demand for P was similar to the amount of mined P used as fertilizer (Figure 2.2). It is important to note, however, that crop and animal feed requirements are also met by manure application or use of weathered or accumulated P from the soil. If, for example, we include the P inputs of pasture and grass feed to animal product P conversion efficiencies, the average global P footprint is approximately 47% higher than when calculated including only mined P sources. Manure application and residual P, when considered as sources of P for crops, are higher than the P requirements we calculated to meet human diet choices globally (Bouwman et al. 2005, Dumas et al. 2011, MacDonald et al. 2011, Sattari et al. 2012, Schipanski and Bennett 2012). Our estimates of per capita P footprints are approximately 50% to 170% higher than in the existing literature. Most of these studies used human P excretion data as a base for consumption (Cordell et al. 2009a, Cordell et al. 2009b). We worked from food availability data, which permitted us to make more detailed temporal and spatial comparisons and to include the P required for all crops produced for food, as opposed to relying only on estimated waste through the food system as in previous studies. Our comprehensive approach also permitted a systematic comparison of national food P requirements as well as analysis of the impact of specific food groups composing the dietary P footprint.

2.6 Conclusion

Dietary choices have played an important role in the increased demand for mineral P fertilizer over the past 50 years. The global P footprint increased between 1961 and 2007, but the magnitude and direction of these changes varied among countries. Furthermore, there is a positive correlation between HDI and national per capita food P footprints, likely because increases in HDI are associated with a more meat-intensive diet. Because meat consumption is the biggest diet contributor to P footprints, future meat consumption may play an important role in the demand for P resources. Decreasing meat consumption in already high P footprint countries could play an important role in sustainable P management strategies, and in synergies with other health and environmental sustainability priorities.

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2.9 Figures and Tables

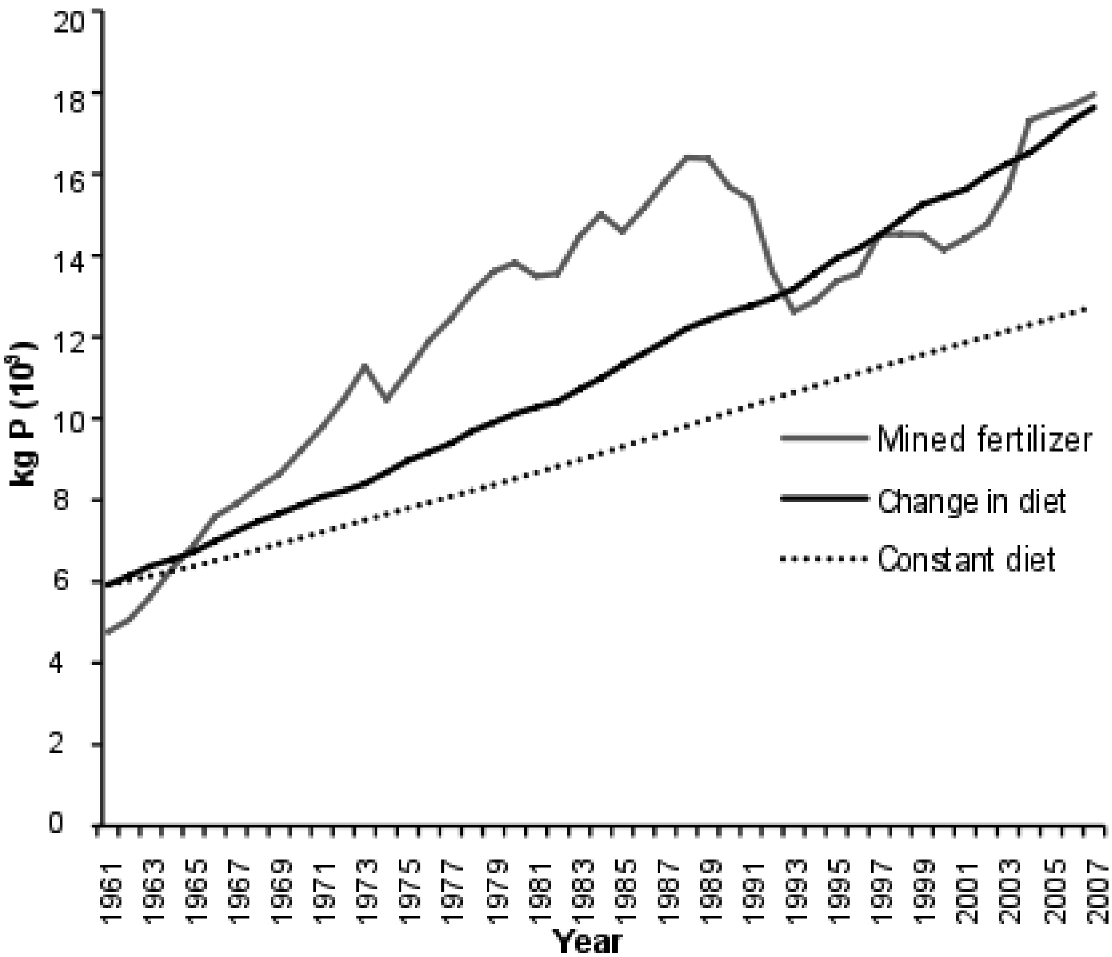


Figure 2.1 Change in total P fertilizer demand and P demand for human diets over time. The grey line represents change in total P mined for fertilizer use (FAO, 2011), the dotted line represents total P required to feed the human population assuming a constant 1961 world average diet, and the black line represents total P required to feed the population given a changing world average diet.

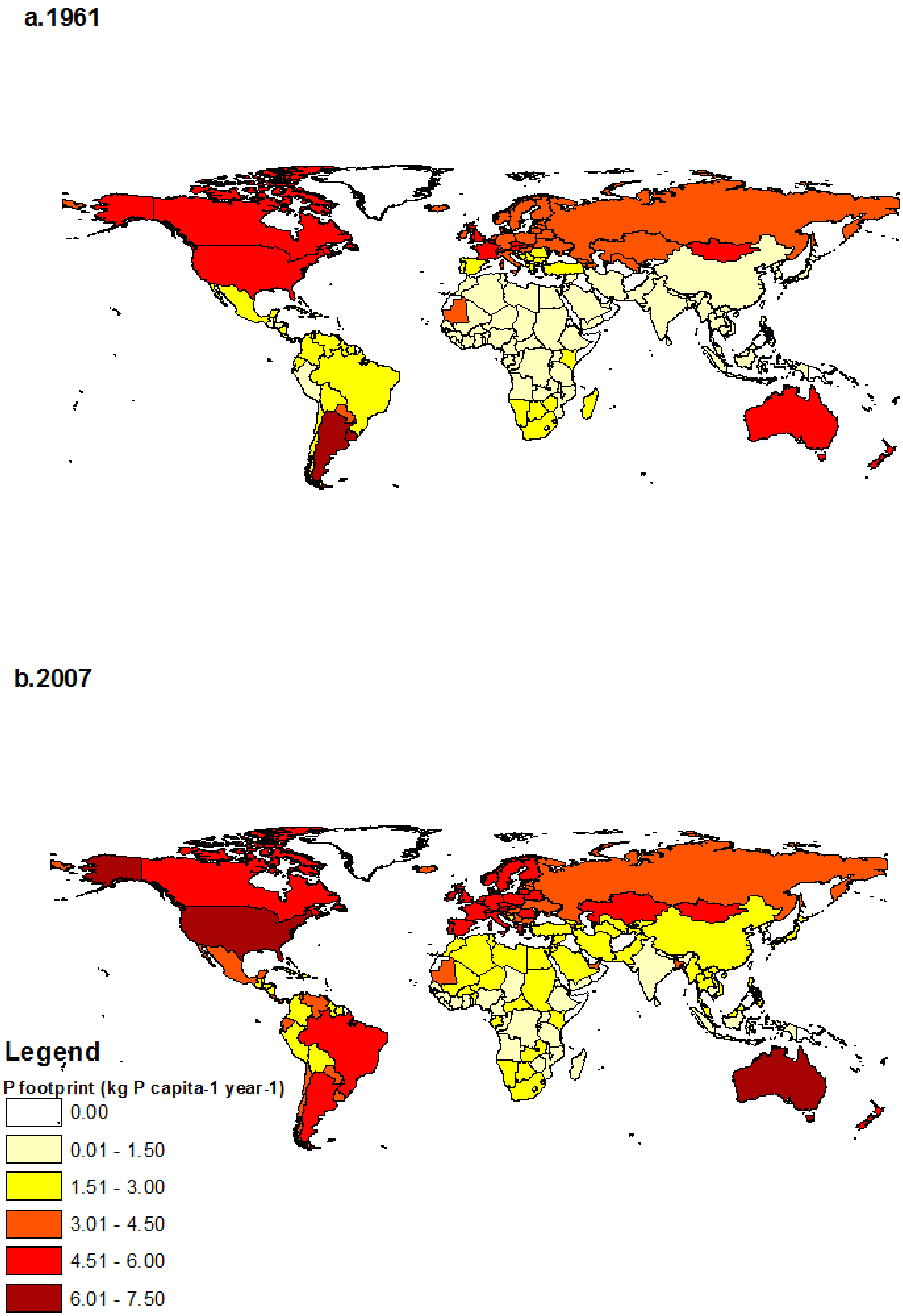


Figure 2.2 Annual P footprint (kg P capita^{-1} year^{-1}) of countries in a. 1961 and b. 2007.

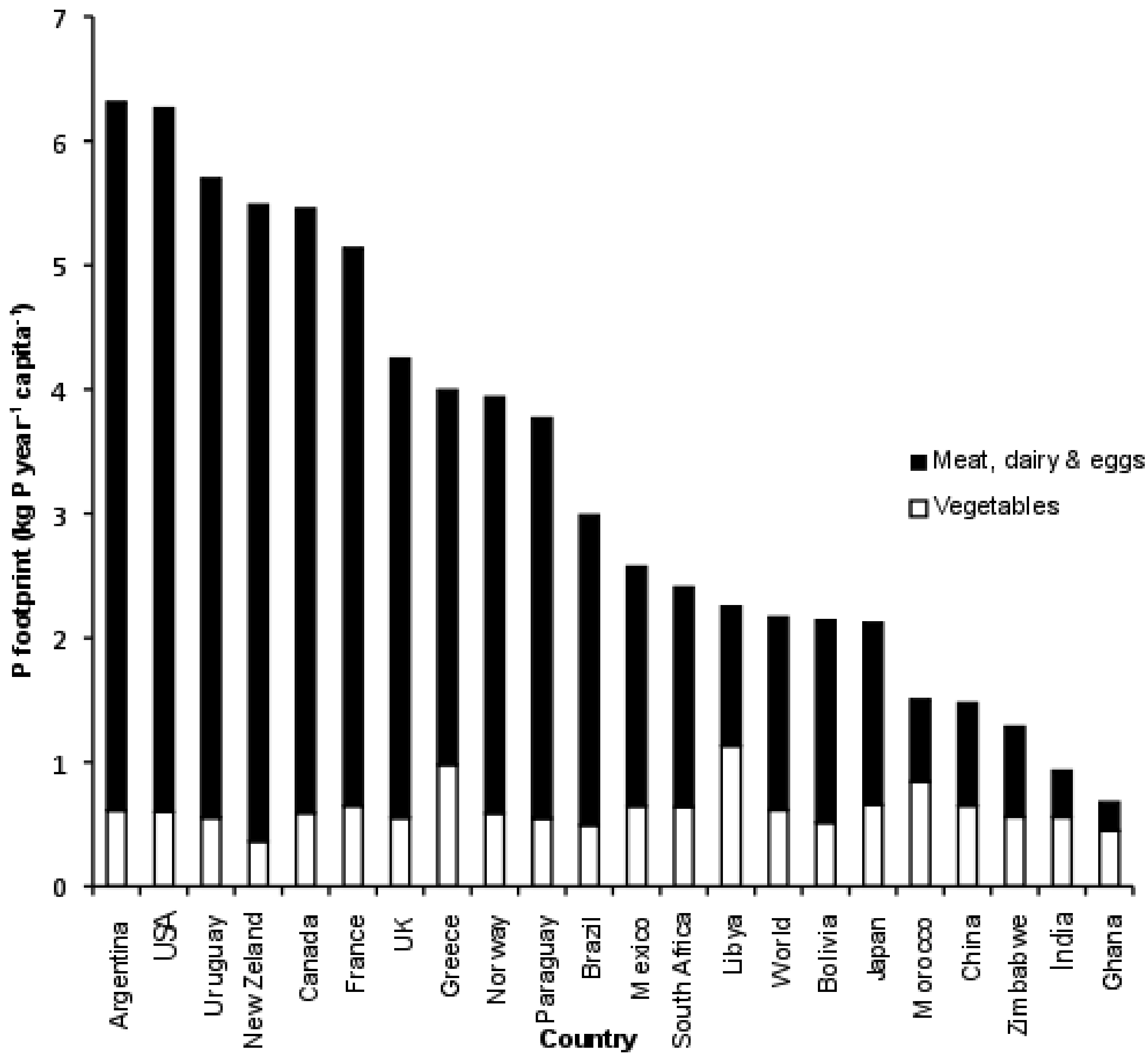


Figure 2.3 Average P footprint between 1961 and 2007, represented as the sum of P required to meet meat, dairy, and egg consumption per capita, as well as that required for vegetable (cereals, fruit, vegetable, starchy roots, sugars, and stimulants) consumption per capita, for selected countries.

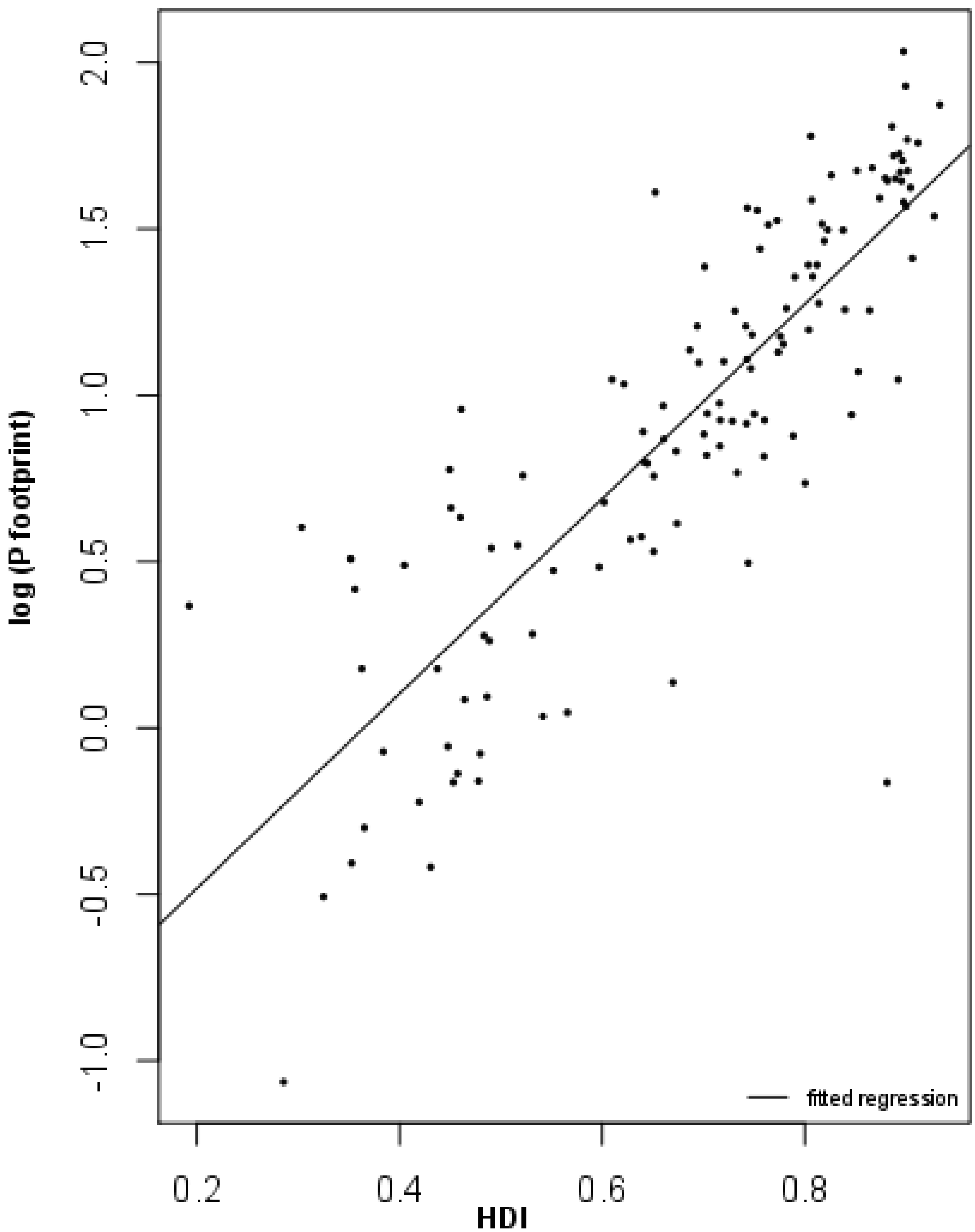


Figure 2.4 Relationships between Human Development Index (HDI) and P footprint values for all available countries in 2007 (fitted regression equation: log of P footprint = 2.92(HDI) – 1.07 (R^2= 0.69 $p < 2.2x10^{-16}$).

Table 2.1 Conversion factors from crop or animal product to mined P requirements by food groups under an averaged global production system. *only P coefficient as feed conversion efficiencies are already reported as dry matter

Food group	Dry matter and phosphorus coefficient	Phosphorus Use Efficiency	Conversion factor (kg P (kg of crop or animal)$^{-1}$)
Cereals	0.003	1.03	0.0029
Starchy Roots	0.0004	1.26	0.0003
Sugars	0.0005	2.19	0.0002
Pulses	0.0002	0.53	0.0004
Treenuts	0.003	0.47	0.0068
Oilcrops	0.004	1.57	0.0025
Vegetables	0.0004	0.30	0.0013
Fruits	.0002	0.33	0.0005
Stimulants	0.004	0.50	0.0076
Bovine Meat	0.003*	0.63	0.0612
Mutton & Goat Meat	0.001*	0.45	0.0094
Pig Meat	0.003*	0.64	0.0316
Poultry Meat	0.004*	0.74	0.0192
Eggs	0.003*	0.74	0.0126
Milk	0.003*	0.60	0.0043

Table 2.2 Equation, variable definitions, units, and references used to calculate P footprints

Equations

$$P[i] = P_{crops}[i] + P_{animals}[i] \quad (1)$$

$$P_{crops} = \sum_{c=1}^{n} \left(f_c z_c d_c \left(\frac{1}{E_c} \right) \right) \quad (2)$$

$$E_c = \sum_{i=1}^{b} \left(\frac{(z_c d_c y_{c\,i})}{F_{c\,i}} \left(\frac{h_i}{h_{global}} \right) \right) \quad (3)$$

$$P_{animals} = \sum_{m=1}^{u} \left(f_m v_m z_{feed\,crop\,mix} \left(\frac{1}{E_{feed\,crop\,mix}} \right) \right) \quad (4)$$

$$v_m = v_{landless} r_{landless} r_k \quad (5)$$

$$z_{feed\,crop\,mix} = \sum_{j=1}^{s} \left(z_k \frac{h_k}{h_j} \frac{h_j}{h_{global}} \right) \quad (6)$$

$$E_{feed\,crop\,mix} = \sum_{j=1}^{s} \left((E_k r) \left(\frac{h_j}{h_{global}} \right) \right) \quad (7)$$

Variable	Description	Units	Reference
General			
P[i]	the sum of all P-fertilizer applied to crops for human consumption in country "i"	kg P $capita^{-1}$ $year^{-1}$	calculated
P_{crops}	the sum of all P fertilizer applied to crops that are for direct human consumption	kg P $capita^{-1}$ $year^{-1}$	calculated
$P_{animals}$	the sum of all the P fertilizer applied to crops that are fed to livestock that is ultimately eaten by humans as meat, eggs, or milk	kg P $capita^{-1}$ $year^{-1}$	calculated
Crops			
n	the total number of crops		FAOSTAT 2011
f_c	food availability for crop or crop category "c"	kg $capita^{-1}$ $year^{-1}$	FAOSTAT 2011
z_c	the P content (as a fraction) in dry matter of crop "c"	dimensionless	USDA 2009, IFA 1992

d_c	the dry matter coefficient for crop “c” used to convert fresh weight of crops to dry weight	dimensionless	Monfreda et al. 2008
E_c	Phosphorus use efficiency of crop “c”	Dimensionless (P in crop/P applied to crop)	calculated
$v_{c\ i}$	average yield of crop “c” from 1995 to 2005 in country “i”	kg ha^{-1}	FAOSTAT 2011
h_i	the average amount of crop “c” produced from 1995 to 2005 in country “i”	tones	FAOSTAT 2011
h_{global}	the amount of crop “c” produced in all countries where data were available for crop “c”	tones	FAOSTAT 2011
Meats and animal products			
f_m	availability of the meat, dairy or egg in category “m”	carcass weight or egg or dairy product output in kg $capita^{-1}$ $year^{-1}$	FAOSTAT 2011
u	total number of animal categories		FAOSTAT 2011,
v_m	feed conversion efficiency of category of animal product “m”	kg of feed (dry matter) kg of $output^{-1}$	Bownman et al. 2005
$v_{landless}$	feed conversion efficiency of animals produced in mixed and landless systems in category “m”	kg of feed (dry matter) kg of $output^{-1}$	(Mekonnen and Hoekstra 2012), Bownman et al. 2005
$r_{landless}$	global average proportion of animals in category “m” that are produced in mixed and landless systems	dimentionless	Bownman et al. 2005 (using 1995 numbers)

r_k	global average proportion of feed in mixed and landless systems for animal category "m" composed of feed categories "k" where k represent food crops, forage, and scavenged feed categories	dimentionless	Bownman et al. 2005 (using 1995 numbers)
$z_{feed\ crop\ mix}$	global average weighted sum of P coefficient of the feed-crop mix for each animal category "m" based on feed-crop mixes in world regions "j"	dimensionless	calculated
$E_{feed\ crop\ mix}$	PUE of the mixture of feed crops fed to livestock for each animal category "m"	dimensionless	calculated
s	total number of world regions		Bouwman et al. 2005 (using 1995 numbers)
h_j	the production of animal category "m" in region "j" in a landless system with feed type "k" where k can be forage, food crops, or scavanged		Bouwman et al. 2005 (using 1995 numbers)
h_{global}	the total global production of animal category "m"		Bouwman et al. 2005 (using 1995 numbers)

Table 2.3 P footprints of developed and developing countries over time. P-values in the bottom row refer to comparisons of P footprints between 1961 and 2007 within each group. P-values in the far right column refer to comparisons between developed and developing country groups for each year.

	Developed countries (kg P $capita^{-1}$ $year^{-1}$)	Developing countries (kg P $capita^{-1}$ $year^{-1}$)	p-value
1961	2.84	1.34	1.27×10^{-10}
2007	4.02	1.70	2.2×10^{-16}
p-value	2.43×10^{-06}	0.001	

Table 2.4 Possible future P consumption based on (a) dietary composition and quantity predictions (Food and Agriculture Organization 2006), reported here in kg of P $capita^{-1}$ $year^{-1}$), and (b) population growth predictions (United Nations 2004), reported as total kg of P necessary to meet global human dietary demands). The current trajectory scenario refers population growth based on current growth rates, and low + vegetarian refers to a scenario with low population growth where instead of FAO dietary composition we used a vegetarian diet where animal protein are replaced with pulses.

Year	a. FAO consumption predictions (kg P $capita^{-1}$ $year^{-1}$)			b. UN population growth scenarios (kg P)				Extreme alternative
	Total P footprint	Meat portion of P footprint	Total vegetarian P footprint	Low	Medium	High	Current trajectory	Low + Vegetarian
2007	2.45	1.32	-	1.61×10^{10}	1.61×10^{10}	1.61×10^{10}	1.61×10^{10}	1.61×10^{10}
2030	3.46	1.55	1.92	2.54×10^{10}	2.71×10^{10}	2.89×10^{10}	3.42×10^{10}	1.41×10^{10}
2050	3.67	1.72	1.97	2.72×10^{10}	3.28×10^{10}	3.91×10^{10}	4.69×10^{10}	1.46×10^{10}

2.10 Supplemental Information

2.10.1 Methods

Calculating P fertilizer use for crops

To calculate PUE based on IFA fertilizer use data and food availability data from FAO, we needed to match or combine data to create matches between IFA data categories and FAO food balance sheet categories. We estimated PUEs for nine FAO food crop categories (i.e. cereals, starchy roots, sugars, pulses, treenuts, oilcrops, vegetables, fruits, and stimulants) rather than for every crop individually. Although we sometimes calculated PUE for individual crops, we aggregated PUE based on the global production of each crop within each of these nine categories, as well as the production of each crop or crop category in each country for which we had IFA data. We choose this aggregated approach for two reasons. First, not all food crops are enumerated individually in the FAO food balance sheets. Using only enumerated crops would give an incomplete picture of human food consumption; using aggregated crop categories was a better method to capture all the information available to us. Second, we wanted to use as much IFA data as possible to give the most accurate representation of PUE possible. By using crop categories, we could use both data from countries where individual crop P application was reported as well as data from countries that included only P application for crop categories. Including more countries allowed us to use PUEs that are more representative of global P use, than only including countries that reported individual crops.

Omitted and transformed categories

We did not include the FAO food balance sheet category 'vegetable oil' because information about food availability in this category was not available for some countries. All countries with no vegetable oil data were developing countries, so including vegetable would accentuate the difference in P footprint values between developed and developing countries. Additionally, vegetable oil plays only a minor role in the overall P footprint of a country. We therefore did not include vegetable oils in our calculation.

For sugars, we used the average P coefficient and PUE of cane and beet sugars weighted by global average production to apply to the reported raw sugar equivalent because countries do not report cane and beet in diet data and instead report a raw sugar equivalent.

Assumptions necessary to use P application rates to calculate PUE

IFA reports some countries' P application data as a rate on 'hectares where fertilizer is applied' and others as an average over all hectares where crops are grown, regardless of whether every hectare is fertilized. We transformed all P application rates to average fertilizer application on all harvested hectares so that all application rates were compatible across all countries.

IFA also reports annual fertilizer application for different years for different countries (varying between 1995 and 2000). In order to combine country data into a global average, we used 1995 to 2000 average values for yields and total production of a crop for each country. The global PUEs used in this paper are a representation of the best data available; however, the level of precision is unequal between crops. For example P application rates for cereals were reported for more countries that application rates for fruits and vegetables; thus, cereals are probably a better representation of the average global PUE. However, we believe that our technique of weighting by production helps alleviate some concern about this since countries that are large producers of a particular crop also tend to report P application rates for that crop.

Calculating animal and animal product consumption P fertilizer requirements

We included beef, pork, poultry, dairy, broilers, sheep and goat as our animal categories when calculating P requirements with regards to meat consumption. We did not include cream and butter themselves in the final P footprint as to avoid double counting as we included whole milk from which these products are derived.

Feed composition for each animal product was reported with respect to four feed categories (food crops, forage, grass, and scavenging), not as a global average for each animal product, but as a proportion of total feed for each animal product by world region. In order to obtain a global average feed composition for each animal product, we thus weighted the feed composition of each world region according to its proportion of total world production of a given animal product as reported in Bownman et al. (2005). In addition to feed composition being reported by world region, feed composition was reported for animals produced in pastoral and in mixed/landless systems within each world region. We weighted the feed composition according to the proportion of total production of an animal product produced in both systems. We used this information to create one global average feed conversion efficiency, one P concentration, and one PUE for each animal category.

Calculating feed-crop P fertilizer use

We calculated the PUE of forage crops using IFA forage-crop P application rates along with world average yields for cereal, oil crops, roots, and pulses, weighted based on the average content of feed (1995-2000, FAO, 2011).

Calculating P footprints that include inputs from pasture and grass in mixed and landless systems

To develop conversion factors for animal products, we determined: 1) the amount of feed necessary to produce each animal product; 2) the composition of this feed; and 3) the amount of P required to grow each feed crop (as per the method using PUE described above). These three steps are detailed below.

1. Calculating required feed quantities for animal production: To convert animal product availability to the amount of feed required to produce it, we used global average feed conversion efficiencies (kg of feed (dry mass) per kg of output (in carcass weight or weight of product for eggs and dairy)) for each animal product category (Mekonnen et al. 2012).

2. Calculating feed composition and P contained in this feed: We converted the amount of feed consumed into the amount of P consumed by animals, recognizing that the amount of P in the feed is dependent on the composition of that feed. Feed can be divided into four diet composition categories: food crops, residue/forage crops, grass, and scavenging (Bownman et al. 2005). For each of these composition categories, we calculated an average P concentration. For the food crop category, P concentration was calculated by weighting the P concentration of food crops used for feed according to the global average production of each one of these crops (FAOSTAT Commodity Balance Sheets). For the forage crop category, we calculated the P concentration by averaging the P concentrations (USDA and NRCS 2009) of crops in the forage crop category (Monfreda et al. 2008). For the grass category, we used the P concentration of grass as reported by the USDA and NRCS (2009). Finally, for the scavenging category, we used the average P concentration for human-destined food crops. Feed composition was reported with respect to these four feed categories, not as a global average for each animal product, but as a proportion of total feed in for each animal product by world region. In order to obtain a global average feed composition for each animal product, we thus weighted the feed composition of each world region according to its proportion of total world production of a given animal product as reported in Bownman et al. (2005). In addition to feed composition being reported by world region, feed composition was reported for animals produced in pastoral and in mixed/landless systems within each world region. We weighted the feed composition according to the proportion of total production of an animal product produced in both systems.

3. Calculating P required for feed crop production: Finally, we converted the amount of P in feed to the P fertilizer required to grow these crops. We weighted the PUE of the four feed composition categories according to their importance to the total feed required to produce each animal category. For the category ‘food crops category eaten by animals’, we used PUE for the cereals crops. We used cereals because they are the most widely used category of food crops diverted from food production as feed (the remaining food crops used are residues; Handy et al. 2005). We calculated the PUE of the residues/forage crop category using IFA (2002) forage crop

P application rates, and used world average yields for cereal, oil crops, roots, and pulses to apply these fertilizer rates on (FAO, 2011), and an unweighted average of dry matter and P coefficients for crops categorized as forage (Monfreda et al. 2008). In order to take into account the importance of categories that were not fertilized (i.e., grasses used in pasture, or by-products, i.e., scavenged crops) we used a neutral PUE value of 1. We thus used a PUE value of 1 for the proportion of animal categories produced with feed from scavenging and grass categories. It is important to note that, although we take into consideration that grass and scavenged crops are not fertilized, these feed types remain important sources of P in the animal diet and omitting them from the total feed and thus P consumed by animals would be inaccurate. By using feed conversion efficiencies that include the amount of grass and scavenged crops required to produce the average kg of meat, or dairy and eggs, animals that require much more feed per kg of meat, such as beef, will have a much higher P conversion factor than other animals even if their diet consists of less fertilized crops.

2.10.2 Results

SI Table 1. P footprints (kg P capita^{-1} year^{-1}) for all available countries in 1961 and 2007 used in this article.

Country/Year	1961	2007
Albania	1.63	4.00
Algeria	1.14	2.05
Angola	0.77	1.26
Antigua and Barbuda	1.80	3.35
Argentina	7.02	5.92
Armenia	3.06	3.01
Australia	5.65	6.51
Austria	4.74	6.10
Azerbaijan	3.06	2.52
Bahamas, The	3.88	4.04
Bangladesh	0.98	3.64
Barbados	2.34	4.54

Country/Year	1961	2007
Belarus	3.06	4.54
Belgium	4.60	5.21
Belize	2.13	2.61
Benin	0.68	2.61
Bermuda	3.71	3.66
Bolivia	1.54	2.64
Bosnia and Herzegovina	2.64	2.99
Botswana	2.00	1.78
Brazil	2.14	4.74
Brunei	1.32	3.51
Bulgaria	2.67	3.09
Burkina Faso	0.75	1.52
Burundi	0.53	0.60
Cambodia	0.87	1.33
Cameroon	0.86	1.10
Canada	5.50	5.86
Cape Verde	0.67	2.45
Central African Republic	0.80	1.66
Chad	1.29	1.20
Chile	2.63	4.02
China	0.58	3.00
Colombia	2.43	2.95
Comoros	1.04	1.05
Congo	0.60	1.04
Congo (DR)	0.59	0.35
Costa Rica	2.10	3.17
Croatia	0.00	3.88
Cuba	2.17	2.56
Cyprus	2.04	4.46
Czech	4.50	4.86

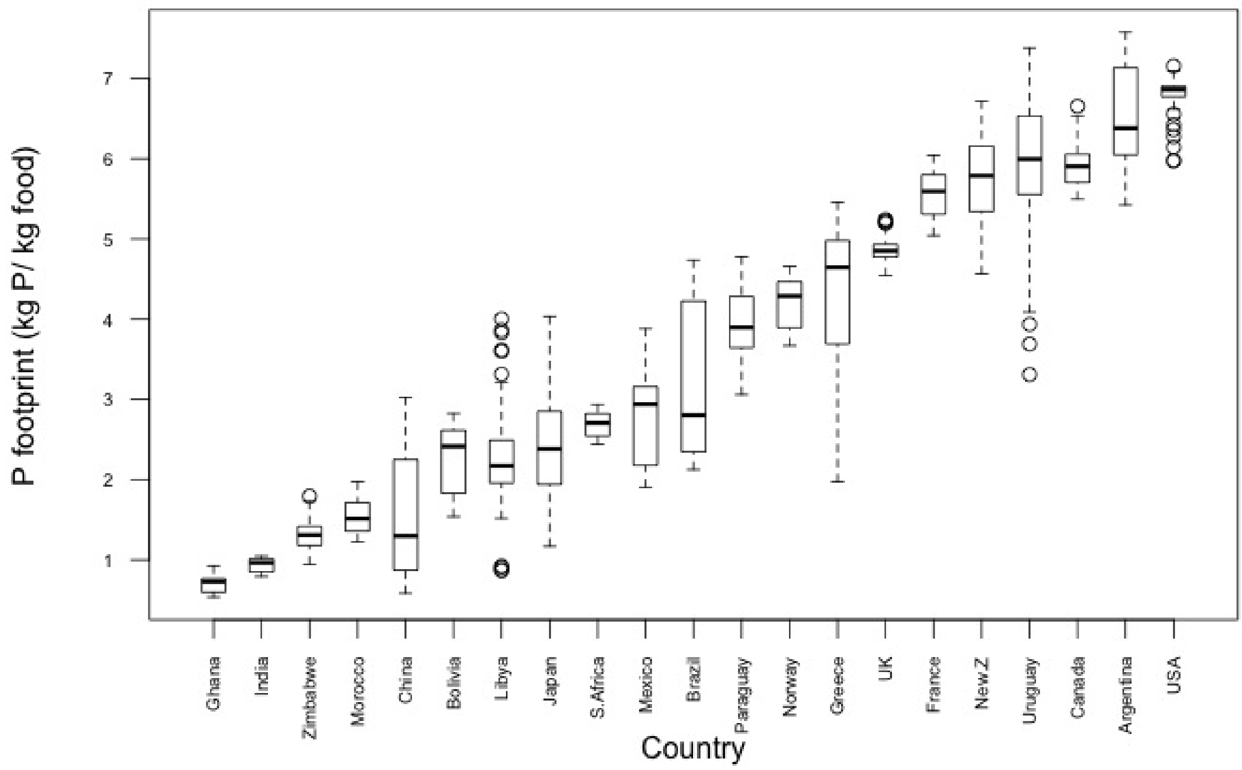
Country/Year	1961	2007
Republic		
Denmark	4.33	6.30
Djibouti	0.96	2.17
Dominica	1.31	3.79
Dominican		
Republic	1.25	2.52
Ecuador	1.66	3.03
Egypt	1.23	2.21
El Salvador	1.31	2.42
Eritrea	0.00	0.48
Estonia	3.06	4.47
Ethiopia	1.27	0.93
Fiji	1.41	2.30
Finland	3.86	5.34
France	5.04	5.32
French		
Polynesia	2.18	5.24
Gabon	0.85	2.18
Gambia, The	1.31	1.36
Georgia	3.06	2.57
Germany	4.45	5.39
Ghana	0.80	0.93
Greece	1.97	5.18
Grenada	1.08	2.40
Guatemala	1.34	1.70
Guinea	0.85	1.01
Guinea-		
Bissau	0.94	1.12
Guyana	1.52	2.13
Haiti	0.66	0.79
Honduras	1.39	2.38
Hungary	3.93	4.32
Iceland	3.51	4.10

Country/Year	1961	2007
India	0.83	1.05
Indonesia	0.60	1.15
Iran (Islamic Republic of)	1.09	2.15
Ireland	4.26	5.80
Israel	2.61	4.92
Italy	3.11	5.58
Ivory Coast	0.87	0.95
Jamaica	1.46	2.65
Japan	1.17	2.85
Jordan	1.06	2.27
Kazakhstan	3.06	4.77
Kenya	1.69	1.72
Kiribati	1.69	2.42
Korea, Peoples Republic of	0.84	0.85
Kuwait	1.79	2.92
Kyrgyzstan	0.00	2.81
Lao People's Democratic Republic	0.97	1.61
Latvia	3.06	4.02
Lebanon	1.64	3.26
Lesotho	1.36	1.94
Liberia	0.80	0.67
Libyan Arab Jamahiriya	0.87	2.30
Lithuania	3.06	4.89
Luxembourg	4.60	7.64
Madagascar	2.14	1.30
Malawi	0.73	0.80
Malaysia	1.16	2.26

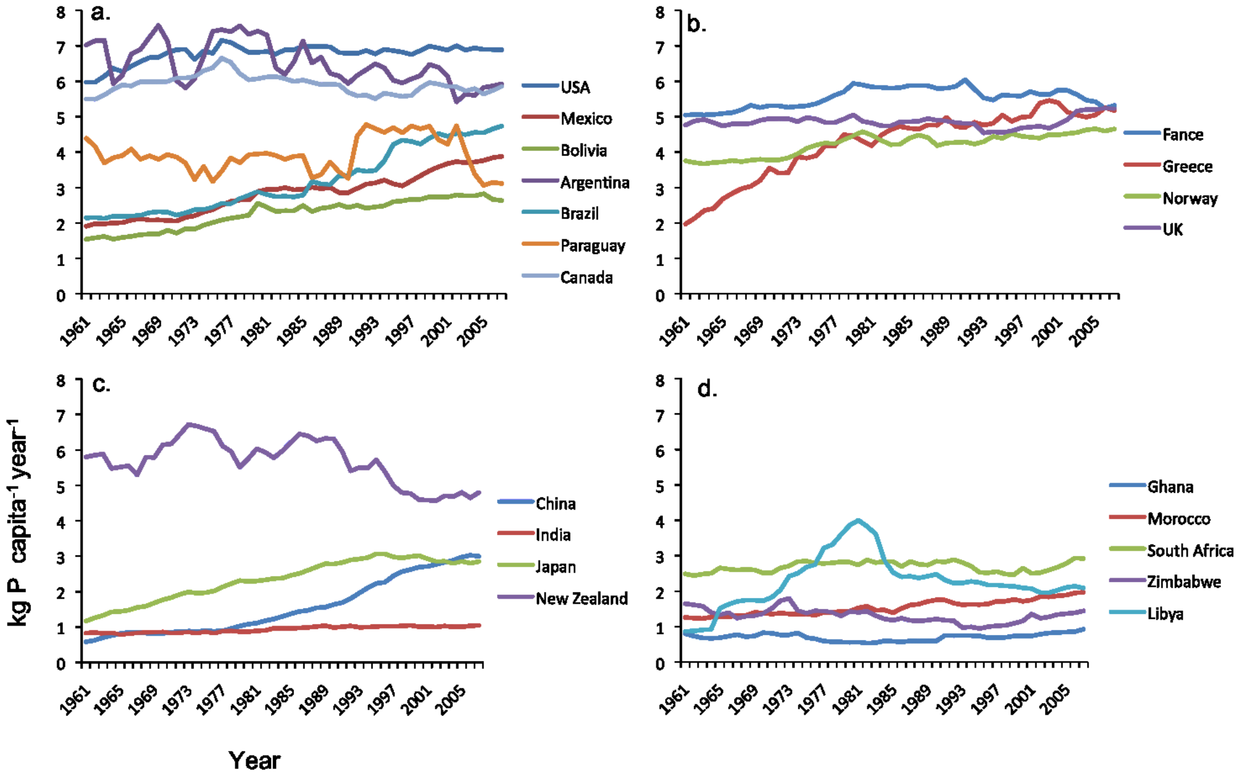
Country/Year	1961	2007
Maldives	0.47	2.82
Mali	1.12	1.66
Malta	2.92	5.27
Mauritania	4.38	3.34
Mauritius	1.15	2.50
Mexico	1.91	3.88
Moldova	3.06	2.44
Mongolia	5.80	5.00
Morocco	1.26	1.97
Mozambique	0.67	0.74
Myanmar	0.74	1.61
Namibia	2.38	2.34
Nepal	0.95	1.32
Netherlands	4.07	5.07
New Caledonia	3.03	3.45
New Zealand	5.80	4.80
Nicaragua	1.62	1.76
Niger	1.22	1.83
Nigeria	0.80	1.09
Norway	3.75	4.65
Pakistan	1.16	1.73
Panama	2.27	3.24
Paraguay	4.39	3.11
Peru	1.35	1.64
Philippines	1.06	1.85
Poland	3.61	4.55
Portugal	1.82	5.34
Romania	2.50	4.60
Russian Federation	3.06	4.22
Rwanda	0.45	0.66
Sao Tome	2.12	2.25

Country/Year	1961	2007
and Principe		
Saudi Arabia	0.75	2.41
Senegal	1.36	1.19
Seychelles	0.98	2.63
Sierra Leone	0.59	0.75
Slovakia	4.50	5.38
Slovenia	0.00	3.58
Solomon		
Islands	1.05	1.22
South Africa	2.49	2.92
Spain	2.12	5.62
Sri Lanka	0.87	1.10
St.		
Christopher-		
Nevis	0.98	2.68
St. Lucia	1.16	3.77
St. Vincent		
and the		
Grenadines	1.02	3.06
Sudan	1.33	1.88
Suriname	1.59	2.15
Swaziland	2.52	2.14
Sweden	4.09	5.50
Switzerland	5.01	5.17
Syrian Arab		
Republic	1.16	1.83
Tajikistan	0.00	1.62
Tanzania		
(United		
Republic of)	1.01	1.03
Thailand	1.31	1.83
Togo	0.75	0.85
Trinidad and	1.79	2.52

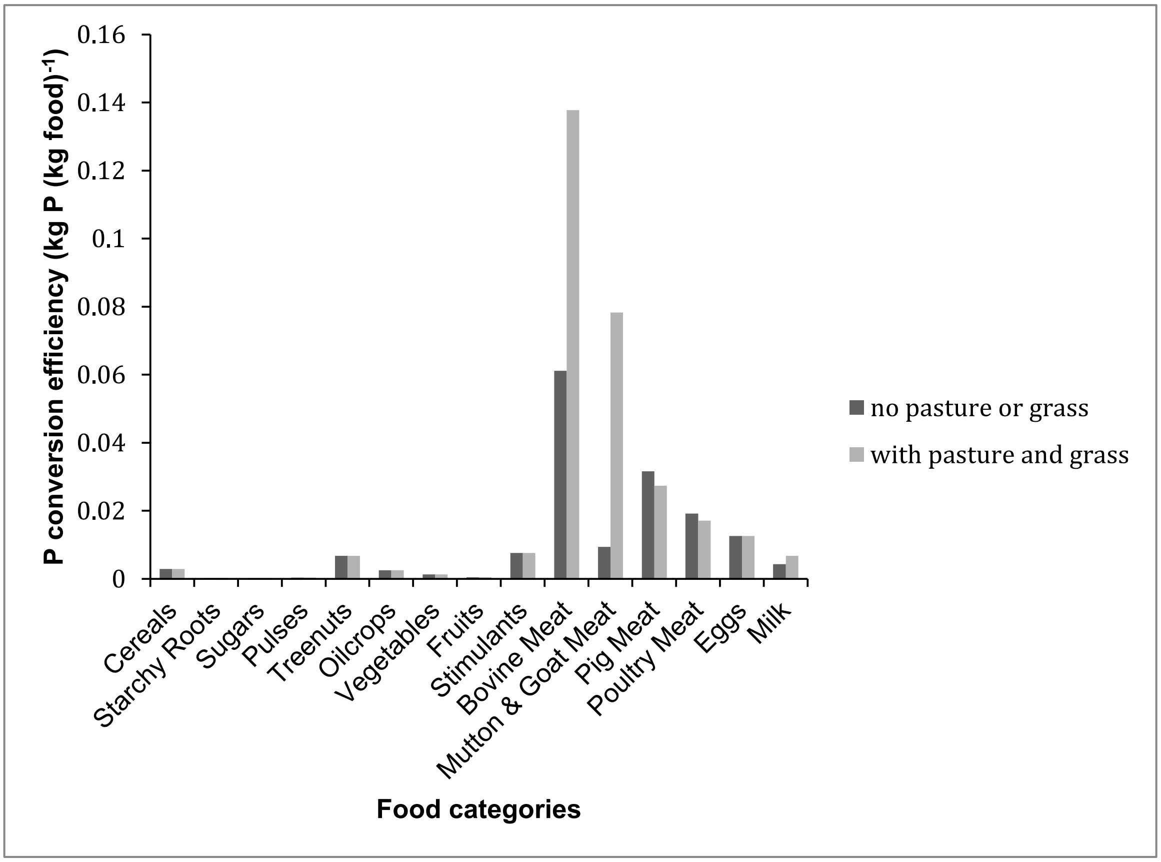
Country/Year	1961	2007
Tobago		
Tunisia	1.18	2.33
Turkey	2.08	2.57
Turkmenistan	0.00	2.96
Uganda	1.16	0.87
Ukraine	3.06	3.50
United Arab		
Emirates	1.45	3.51
United		
Kingdom	4.76	5.22
United States	0.54	6.89
Uruguay	6.80	3.31
Uzbekistan	3.06	2.85
Vanuatu	1.55	2.16
Venezuela	2.47	3.53
Vietnam	0.96	2.22
Western		
Samoa	1.98	3.34
Yemen	0.92	0.54
Yugoslavia	2.64	3.34
Zambia	1.35	1.63
Zimbabwe	1.65	1.44
World	1.91	2.65



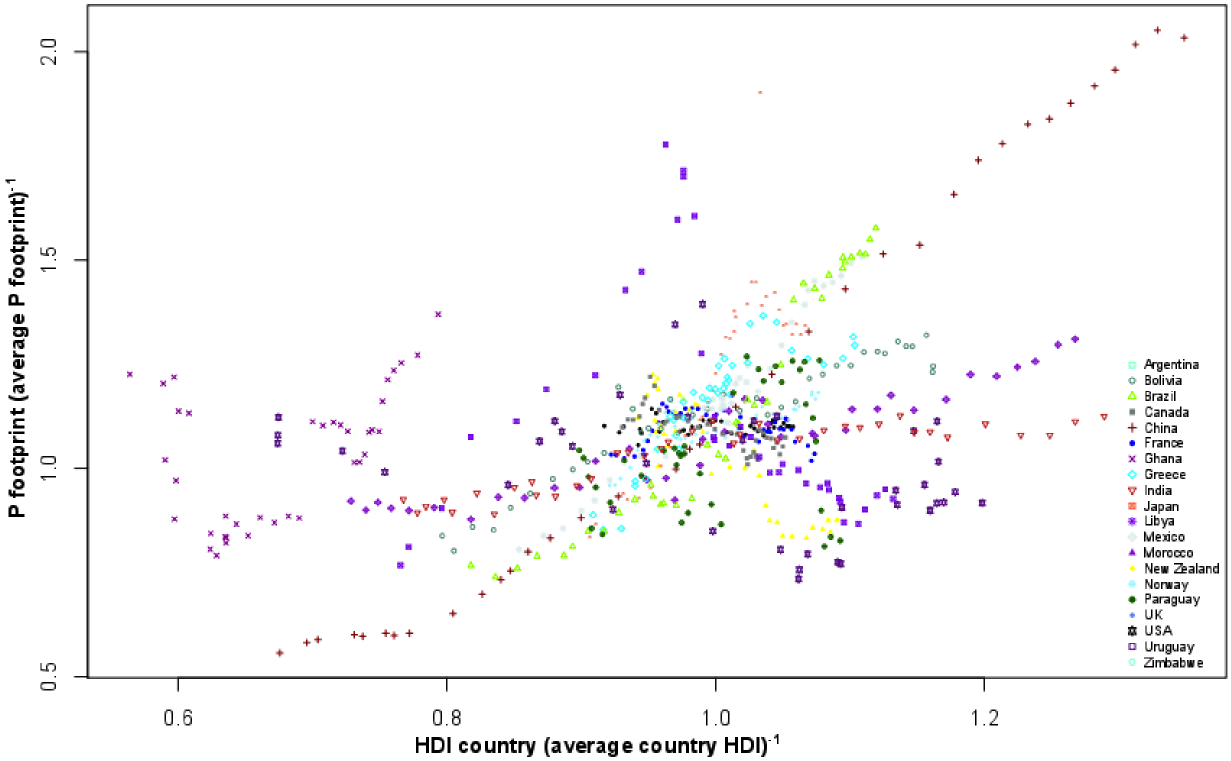
SI Figure 1. P footprint boxplot (mean, inter-quartile range, and outliers) showing the range of all data by country from 1961 to 2007 for selected countries.



SI Figure 2. P footprints over time for selected countries in a. North America, b. Europe, c. Asia and Oceania, d. Africa.



SI Figure 3. The influence and inclusion of P inputs from pasture fed animals and grass fed animals in mixed and landless systems on the P conversion efficiencies used to calculate P footprints. The conversion efficiencies of animal groups including grass and pasture assume that grass is not fertilized, thus use a P use efficiency value of 1, but use feed conversion efficiencies in Mekonen et al. (2012) that include the amount of P consumed by animals through grass.



SI Figure 4. Relationships between Human Development Index (HDI) and P footprint values for 18 countries annually from 1961 to 2007 where countries are color coded by continent (red is Asia, black/grey is North America, blue is Europe, green is South and Central America, Yellow is Oceania, and purple is Africa).

2.10.3 References

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CONNECTING STATEMENT

In Chapter 2, I considered the importance of dietary choices in driving the changing global demand for mined P between 1961 and 2007. My results clearly demonstrate that dietary choices are a key driver of P demand globally, with meat having the largest P footprint of any product. Wealthier countries, where meat consumption was high, had the highest per capita P dietary footprints. Countries with rapidly increasing wealth, such as China, tend to also have rapidly increasing meat consumption, driving marked increases in per capita P footprints in those countries. Decreasing meat consumption in some wealthier countries may be a viable mean by which to reduce P demand and thus increase P sustainability. Knowing that individual choices are important drivers of national and even global P consumption, I turn my focus next to cities, locations where many people live and many choices happen in a small area. In Chapter 3, I determine the quantitative flows of P in the food system and urban agriculture system of the island of Montreal (Canada). Chapter 3 is the first completed P budget for Montreal, and is, importantly, the first time the role of urban agriculture has been quantified in terms of its role in P cycling and potential for recycling in a developed world city.

3 PHOSPHORUS CYCLING IN THE FOOD AND URBAN AGRICULTURAL SYSTEMS OF THE ISLAND OF MONTREAL

This chapter is under consideration for publication: Geneviève S Metson, Elena M Bennett. Phosphorus cycling Montreal's food and urban agriculture systems. Plos One.

3.1 Abstract

Cities are a key system in anthropogenic phosphorus (P) cycling because they concentrate both P demand and waste production. Urban agriculture (UA) has been proposed as a means to improve P management by recycling cities' P-rich waste into local food production. However, we have a limited understanding of the role UA currently plays in the P cycle of cities or its potential to recycle local P waste. We quantified the role of UA in the food P system in Montreal, Canada to explore the potential for UA to recycle local P waste. We used substance flow analysis to quantify P flows in the overall food system of Montreal, using government and peer-review literature as data sources, and in its UA system for 2012, obtaining P data and information on UA practices primarily through 164 surveys with local UA practitioners. In 2012 Montreal imported 3.5 Gg of P in food, of which 2.63 Gg ultimately accumulated in landfills, 0.36 Gg were discharged to local waters, and only 0.09 Gg were recycled through composting. We found that current UA contributes only 0.44% of the P consumed as food in the city. However, within the UA system, 73% of inputs applied to soil were from recycled sources. Thus, although UA is a small sub-system in the overall P cycle of the city, it may prove to be a valuable asset to increase urban P sustainability by becoming a catalyst for increased P recycling in the city.

3.2 Introduction

People have accelerated the global phosphorus (P) cycle and have altered the usually tight nature of ecosystem P recycling through mining of P for fertilizer use (Bennett et al. 2001). P is an essential input to agricultural production, which makes its financial, geopolitical, and physical availability an important determinant in food security around the world (Wyant et al. 2013). By the year 2000, humans had accelerated P cycling to 3 times its natural extraction rate by mining, primarily to produce fertilizers for agricultural production (Smil 2000). In the process, P runoff from fields and cities caused nutrient loading pollution in downstream waterways, leading to widespread eutrophication (Carpenter et al. 1998, Diaz 2001).

Current management of P is problematic from both a mineral scarcity and a water pollution perspective (Childers et al. 2011), yet our understanding of the best ways to more sustainably manage P through our food system remains incomplete (Elser and Bennett 2011). We still lack information about the real potential of proposed solutions to increase P efficiency and recycling within the social, technological, and biophysical context of particular locations. As such, quantifying how we currently manage P with location specific-data, and evaluating how we can manage P more sustainably in the future, are key questions for improving management of this important nutrient.

Cities, which concentrate people, concentrate both the demand for food and the production of waste, thus clustering P flows on the landscape. Such concentration offers opportunities for the capture and recycling of P, thus reducing pollution while also decreasing dependence on mined sources of P. Urban and peri-urban agriculture in particular can play a key role in recycling P-waste back into food production at the local scale because it places food production (a P consumer) close to waste production (a P producer). Smit and Nasr (1992) acknowledge the lost resources urban agriculture (UA) can utilize, and studies about UA in Ghana and Ethiopia have highlighted its role in addressing both food security and sanitation issues through nutrient recycling (Drechsel et al. 2007). Low technology solutions, especially composting, and high technology solutions, including struvite fertilizer production from wastewater plants, can facilitate safe recovery and reuse of P in urban environments (Cordell et al. 2011).

However, the potential of cities, and of UA in particular, to increase P recycling, and thus sustainable P management, has not been quantified in the developing world. There exist some formal studies on the current role and future capacity of UA and peri-urban agriculture in urban P recycling in the developing world (e.g, Drechsel et al. (2007)). However, existing work on P recycling through local agriculture in the developed world has mostly remained in the realm of possible future scenarios, often using assumptions based on rural agricultural practices (e.g., Baker (2011)). While UA has been studied in the developed world context, existing studies have not focused on P, but rather on other aspects of UA including social benefits (e.g., Barthel et al. (2013), potential cultivated area and fruit and vegetable production (e.g., Ackerman (2011), MacRae et al. (2010)), environmental contamination and possible health risks (e.g., McClintock et al. (2013), Mitchell et al. (2014), von Hoffen and Säumel (2014)).

Here, we examine two key systems in urban P cycling on the island of Montreal, Canada (Figure 3.1): the Montreal island food system (i.e., all food imported and consumed, and all food and sewage waste produced on the island) and the UA system (i.e., the fertilizers imported, crops harvested, animals raised, and organic waste produced through UA on the island) to better understand the current and potential role of UA in urban P cycling and recycling.

3.3 Methods

3.3.1 P flow calculation

We used substance flow analysis (SFA, Kennedy et al. 2010) to quantify P flows for the year 2012 through the food system (Figure 3.2), and through the UA system on the island of Montreal (Figure 3.3). Montreal Island (approximately 500 km^2, population 1.98 million in 2012) is located in the Saint-Lawrence River (Figure 3.1, Communuaté Urbaine de Montréal 1996). The food system and the UA system on the island of Montreal have unique P flows, and thus flow calculations, data collection, and necessary assumptions between the two SFA analyses differed. In particular, our analysis of the food system focuses on flows into and out of the island in food and organic waste, while our analysis of the UA system focuses on the use and sources of P for UA on the island of Montreal. Each flow, in both systems, was calculated by multiplying the weight of the material by its P concentration.

For the Montreal food system, we quantified P in food imports to the island (1), food consumed on the island (2), human urine and feces produced on the island (3), sewage waste going to the wastewater treatment plant (which combines human waste with industrial waste, 4), sewage treatment plant losses to the Saint-Lawrence river (5), biosolids sent to landfill (6), septic storage (7), food and green waste produced on island (8), food and green waste recycled through compost (9), and food and green waste produced sent to landfill (10, numbers refer to Figure 3.2 and Table 3.1). We considered both food and green organic waste in the calculation of flows 7, 8, and 9 because the City waste management department does not fully differentiate them in their reports and we wanted to use the most accurate site-specific information possible, and because compost production from food waste requires the addition of high carbon material like green/yard waste when done at small scales (Cooperband 2002). The P concentrations for flows were found in published literature and government reports, and quantities (mass) were obtained through official government reports (Table 3.1). Because different data sources were used to calculate each P flow, some discrepancies between inputs, outputs and wasted P are present in our study of the Montreal food system. We used site-specific information whenever possible, with regional or national averages to supplement site-specific information as needed.

For the UA system (the area used to produce human food, and feed and pasture for livestock on the island), we quantified P in fertilizer imports (a), harvested crops (b), compost and manure reused on the island (c), imported feed and animal supplements (d), food and feed exported (e), and food from local UA production consumed on the island (f, letters refer to Figure 3.3 and Table 3.2). Because little quantitative data about UA in Montreal existed, it was necessary to survey local practitioners to get information on: the area under production, the type of substrate used, the type and quantity of P applied to farms and gardens, the amount of harvested crops and animal products, and the organic waste recycled or leaving the system. We determined whether the P flows entering and leaving the UA system (referred to as a budget) were balanced (with inputs equaling outputs), in positive P balance (inputs exceeding outputs, causing the system to accumulate P), or in negative P balance (outputs larger than inputs of P).

3.3.2 Urban agriculture system data collection and processing

We designed a survey to obtain quantitative data on P flows and information on general nutrient management practices (see SI material for full survey administered and more information on sampling strategies). We conducted in-person surveys with larger commercial farmers (10 surveys in total), private and community gardeners (83), and organizations managing collective, institutional, and work-place gardens (50) between April and November 2013. We then scaled survey results on P flows to match the estimated area under UA production to create the P budget. McGill University Research Ethical Board approved the protocol for administering the survey, survey questions, and data management and storage protocols (REB File # 995-0213). Written consent was obtained whenever possible through signature, although oral consent was also approved, and was documented by the researcher checking the consent box on the survey form.

We divided UA actors into three categories based on the size of operation and the type of management: 1) farms, which included for-profit enterprises and large-scale university farms, 2) collective, institutional, and business gardens, which included gardens where many individuals may participate in the gardening, but decisions about fertilization, management, and harvest are made collectively or centrally by an organization or agronomic advisor, and 3) community and private citizen gardens, where each individual gardener makes decisions about his/her plot of cultivated land. We used different sampling strategies for these three categories. For groups 1 and 2, we developed an initial list of UA practitioners to survey (based on information from the Office de consultation publique de Montréal (2012)) and used the snowball method (Yin 2003) to ensure we had contacted as many relevant actors as possible. The large number of community and private gardens and lack of comprehensive public registry necessitated more opportunistic sampling. For community gardens, we communicated with garden presidents to gain access to the grounds and were successful in getting at least one garden in each of 13 boroughs (out of a total of 19 city boroughs). For private gardens, we contacted possible respondents through gardening electronic mailing lists and snowball sampling, ultimately obtaining 33 respondents. In addition to differentiating between three types of actors managing UA, we also differentiated between three types of substrate use (gardening in 1) exclusively soil (directly on the ground), 2) exclusively alternative substrate (in containers or on a roof), or 3) mixed (both on the ground, and in containers or on a roof)). Some conversions and assumptions were necessary to transform survey answers into P flux values into and out of the gardens, and to calculate P flows for the island as a whole. Table 3.2 describes P flow calculations and assumptions, and Table 3.3 describes data sources for density of materials, dry matter content, and P content used when site-specific information was not available.

We calculated the total area under UA production to scale our survey results to the whole Montreal UA system (Tables 3.2 and 3.4). To do this, we used different assumptions and data sources for the area in each type of UA. For the two farms missing from our surveys, and for which we therefore were lacking area information, area data was found on the *Agriculture Montréal* website (CRAPAUD et al. 2013), where farms, organizations, and individuals are invited to register the location and name of their garden into a map database and can include the area under cultivation (consulted January 14th 2014)). City data indicates that about 42 % of households participate in UA (Ville de Montréal 2013b). For those households practicing UA in yards (i.e., not on roofs or balconies) according to City data, we multiplied the number of households by the average area of a vegetable garden in the USA (56 m^2 or 4% of the average American yard (Butterfield 2009)). We chose to use the size of the average American yard garden as it was derived from a larger (and thus more robust) dataset, and this area is still comparable to what other smaller studies have found. In Toronto, surveys indicated that the average vegetable and fruit garden in private yards was 41m^2 (Kortright and Wakefield 2011), and that such private gardens could represent approximately 1% of the Toronto area (MacRae et al. 2010). In Chicago, mapping through Google earth and GIS revealed that home private gardens represented 3 times the area of community garden spaces, and that these private garden areas are often overlooked in estimates because they are hard to map (Taylor and Lovell 2012). Based on our estimates of private garden size, the area they occupy is approximately twice that of known community gardens, and about 2.7% of the total area of the island and is thus within the range of possibility. For those households practicing UA on their balcony or roof, we multiplied the number of households by the area of four *Alternatives* gardening containers (4*0.24m^2, *Alternatives* containers are commonly used in Montreal and can be made at home from a city recycling bin). Four containers represents just under 1m^2 which can fit on balconies in Montreal and represents the minimum space allocated by any of our survey respondents that cultivated in containers, and is thus a conservative estimate of the area under cultivation on roofs and balconies. The total area under production in community gardens was provided by the City of Montreal (Office de consultation publique de Montréal 2012). Area data for collective gardens that we did not survey were found on the *Agriculture Montréal* website (CRAPAUD et al. 2013). For those collective gardens that did not report an area under production but were listed on the website, we used the average area of all collective gardens that did report area (90.84m^2). Animal flows were added separately (i.e., we used survey data directly without scaling) because we surveyed all large-scale farms with animals.

3.3.3 Future Scenarios

The Quebec provincial government has mandated that 100% of all organic waste be recycled by 2020 (CMM 2008, MDDEP 2009). To determine how UA might contribute to recycling municipal P in Montreal to attain this goal, we calculated the following:

1. The amount of P that could be recycled if all P applied to the current area in UA originated from on-island recycled sources.
2. The UA area necessary to recycle all P in food and yard waste currently produced on the island.
3. The UA area necessary to recycle P in food and yard waste if we decreased organic waste production by 50%.

To do this sustainably requires balanced P budgets. Thus, in all scenarios we assume P balance, where P harvested per m^2 is equal to P applied. P harvested per m^2 is calculated based on our survey results (weighted by the estimated area of each type of UA, i.e., average P harvest for our P budget).

3.4 Results and Discussion

3.4.1 Montreal food system

In 2012, 3.51 Gg P were imported to the island of Montreal in food, 0.37 Gg P was exported in wastewater to the Saint-Lawrence river, and 2.63 Gg P were exported to landfills (Figure 3.2). The majority of P entering the island system ultimately accumulated in landfills because the majority of solid organic waste (89%) and all incinerated biosolids from the wastewater treatment plant were disposed of in this manner. A small amount of sewage waste was treated by septic systems and this P was considered to be stored in the ground on the island (0.08 Gg). Six percent of P as organic waste was composted or left on soil and thus recycled within the system as this P was returned to soil on the island as fertilizer (0.09 Gg of P).

3.4.2 Montreal UA system within the food system

We now move from the food system for the entire island to the smaller Montreal UA system, which accumulated P with a net positive soil P balance of 0.32 Gg P yr^{-1}. That is, UA practitioners harvested less P in food and feed (0.01 Gg P yr^{-1}) than was applied to soils in 2012 (0.33 Gg P yr^{-1}, Figure 3.3). In addition to imported fertilizers (0.09 Gg P yr^{-1}), 0.002 Gg of P were imported as feed to supplement the 0.003 Gg of P produced as feed on island, and P ingested by animals on pasture. Only 27% of P inputs applied to garden and agricultural soils were imported to the island, while the vast majority (73%) came from on-island sources, including green-waste compost, vermicompost, and manure. Of the P harvested in crops grown on the island, 48% was consumed on the island as food (fruits, vegetables, milk, and eggs), 22% was consumed as feed on island, and 28% was exported (mostly as soy and corn). Excess manure (48% of manure produced on island) was exported to off-island farms.

Currently, P cycling in Montreal's UA system is only a very small part of the overall food system of Montreal. P inputs to the UA system only represent 2.58% of the P imported to Montreal in the larger food system. P in crops, milk, and eggs produced on the island through UA represent only 0.43% of the food distributed to people through grocery stores and restaurants. In other words, the UA system is much smaller than the food system.

However, the UA system favors the use of recycled P sources over those purchased from off island, making it an important P recycler on the island. Currently, 6% of food and yard waste P is recycled through composting in the food system of the island. In contrast, the amount of P recycled into the UA system represents about 19% of P found in all yard and food waste on the island, even though UA only occupies 3.5% of the island area (Figure 3.4, noting however that UA currently applies more P than is harvested). It is important to acknowledge, that the UA system and the food system calculations do not perfectly match up because of the use of different data sources, and thus comparing P recycled in the two systems must be done with caution. Still, we can say that the UA system does seem to proportionally recycle more P than the Montreal food system as a whole.

3.4.3 Diversity of P management within UA

Our survey results indicated similarities in the use of recycled P sources, but differences in the overall P application relative to harvest, among types of UA (farms, collective gardens, and private and community gardens). The majority of survey respondents practiced some form of P recycling through manure recycling, composting, or leaving residues on soil (83%). Plant-based compost was an important recycled P input for collective and private and community gardens, while recycled on-island manure was the largest contributor to P inputs on farms. The P balance was negative for the area cultivated by large farms, and P as harvested crop per area (i.e., yields) was much higher on farms than in other management types (SI Figure 2 and SI Table 1). P balances were positive in both collective gardens and private and community gardens, indicating over-application of P relative to current yields.

P management also differed among substrate types (soil, mixed, and alternative) in collective and private and community gardens. Respondents who cultivated in soil or in mixed substrates used more on-island compost, and thus recycled more P, than respondents that cultivated exclusively in alternative substrates (i.e., in containers or on roofs). The P balances of respondents who used mixed and alternative substrates were higher than those cultivating exclusively in soil. Still, P applied exceeded P harvested for all types of substrates (SI Figure 3 and SI Table 2) in collective, private, and community gardens.

3.4.4 Potential for UA to recycle more P from the food system

Two ways to increase P recycling on the island are to increase the area under cultivation and to increase the percentage of P inputs to UA from on-island recycled sources. Increasing the area under cultivation would increase the amount of P recycled; however, it could not recycle all P used on the island. The amount of UA area necessary for Montreal to recycle all of Montreal's food and yard waste P is larger than the island itself (Figure 3.4). It would require 1850 km^2 of UA (an area nearly four times larger than the island of Montreal) to utilize all P waste currently produced. Even if Montreal were to produce 50% less P as organic waste (via increasing efficiency in the food system), the area needed for UA to utilize all waste P would still be almost twice the area of the island. Thus, UA alone, under current yields and balanced P application, cannot recycle current P losses in the system. Ultimately, partnerships with off-island peri-urban farms, which are considerably larger (average size of 1.13 km^2 in Quebec (Satistics Canada 2007)), could increase recycling of local P and thus help the city meet the 100% organic waste recycling goal set by the provincial government.

The area under UA could be increased to recycle more P, even if this would not recycle *all* P. Montreal could potentially cultivate seven times the area currently in UA (thus 25% of the island) if 27% of the area zoned as low and medium density residential land use, all vacant land, and 10% of green spaces were under UA production. This potential is based on the easiest increases (i.e., spaces that would not require large technological interventions to implement UA and where medium to large garden areas are available). Such potential increase in UA, assuming a balanced-P scenario, could recycle however only 6.8% of P in food and yard waste produced on the island. Additionally, although UA may provide multiple benefits, there are competing uses and priorities for all of these spaces within the planning context; thus, conversion of this land to UA remains unlikely (Lovell 2010).

Increasing the percentage of P inputs to UA from on-island recycled sources is possible, but may not increase the overall P recycling in Montreal. Currently UA applies more P than is harvested, thus recycling more P than would be possible with a balanced-P scenario. If UA practitioners ensured balanced P budgets and used only on-island recycled P sources to meet P demand of harvested crops, they could recycle 0.87% of food- and yard-waste P currently produced (instead of the estimated 19% currently recycled based on our survey data, Figure 3.4). However, increasing yields, and thus P uptake, could increase the potential demand for recycled P in UA.

Urban agriculture's potential for P recycling through increased cultivated area may be affected by the type of UA and the type of substrate used in these new spaces. Our survey results indicate that collective, community, and private gardeners favored compost as a source of P. Increasing UA area with these management types could thus be favorable for using more on-island recycled P in compost. However, a phone survey by the city of Montreal on UA practices indicated that only 23% of Montreal UA practitioners composted (Ville de Montréal 2013b). P recycling may thus not be as high as our survey results indicate, and changes in nutrient management practices would be needed to ensure high P recycling in these gardens. Altering gardening practices may be especially important if increases in UA happen in container or rooftop gardens. Our survey results indicate that P inputs came mostly from off-island imported sources when gardeners used mixed, container, or roof growing surfaces. Growing medium and fertilization guidelines for containers or roof gardens often suggest lightweight commercial amendments which do not explicitly include local compost (e.g., Langellotto et al. (2011)). It may thus be necessary to look for on-island recycling methods that concentrate nutrients more than composting (for example struvite production from wastewater (Jeanmaire and Evans 2001, Cordell et al. 2011)), or alter guidelines when possible.

Even if Montreal used only recycled P in UA and increased UA area, UA alone could not recycle all of the P waste in the food system. The potential area available on the island for cultivation, and thus the demand for P, is simply too small. UA does, however, currently play a disproportionately large role in P recycling on a per area basis. As such, even if quantitatively small, P recycling through UA could serve as a catalyst for recycling at broader scales if citizens understand and support small and large-scale composting through their gardening practices.

3.5 Conclusion

Issues of P scarcity for food production and P pollution in aquatic ecosystems make sustainable P management a pressing issue from the global to the local scale. Theoretically, cities have an important role to play in increasing P sustainability as they concentrate both P demand and waste production. UA has the potential to contribute to sustainable P management by facilitating the reuse of P in near-by gardens and farms. We used the island of Montreal as a case study to investigate the current P recycling in the food system and UA system to examine how much of this potential is used. In Montreal, the current P food system is dependent on imported food, and the majority of P waste is stored in landfills, with only a very small amount of P recycled as compost. UA is a small part of P cycling in Montreal's overall food system. Even though the majority of P inputs to UA come from recycled sources, the food and feed harvested still only represents only a small fraction of Montreal's P food imports. Although UA in Montreal could not possibly recycle all P from on-island organic waste, the small quantitative role UA currently plays may still have potential as a catalyst for broader action because the majority of surveyed UA practitioners recycle some P. This study serves as a quantitative benchmark to understand P cycling in the food and UA systems, and to monitor the effect of changes in policies and practices over time in Montreal. As key ecosystems on our landscape, understanding and monitoring nutrient cycling in cities is necessary for sustainable resource management, and our Montreal case study demonstrates that although cities have potential to recycle P internally through UA and back to peri-urban agricultural land, this potential is not always fully utilized.

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3.8 Figures and Tables

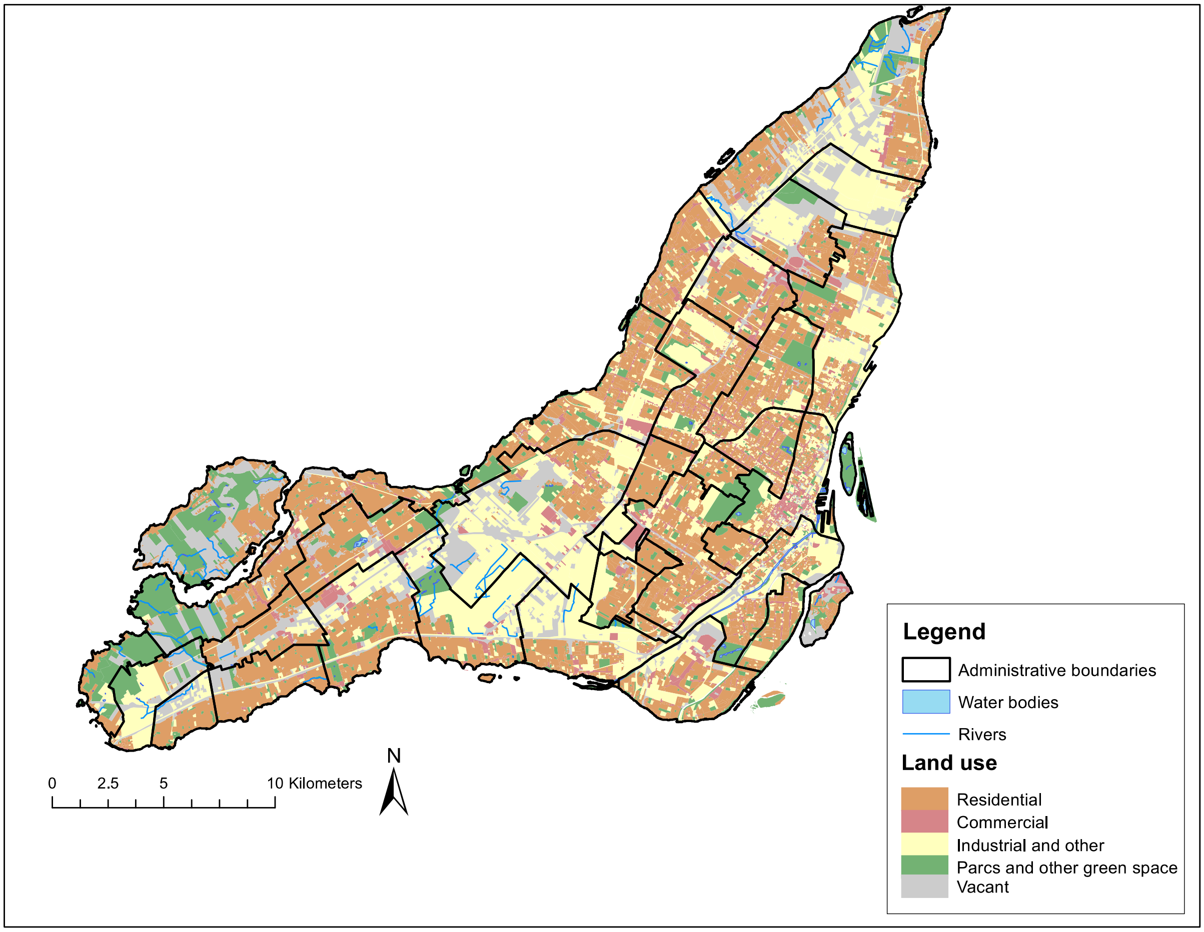


Figure 3.1 Land uses on the island of Montreal. The island of Montreal is aproximately 38% residential, 12% green space, 14% vacant lots, and 18% industrial and commercial land uses. residential land-use includes high, medium, and low density housing, commercial land use includes malls, service-industry buildings, and business district, industry and other land use includes light and heavy industry, quarries, public and education institutions, landfills, and service utility areas, parks and other green space land use includes golf courses, cemeteries, regional and city parks, natural reserves, and rural sites (Communuaté Urbaine de Montréal 1996). Municipalities and borough limits are indicated by the black administrative boundaries.

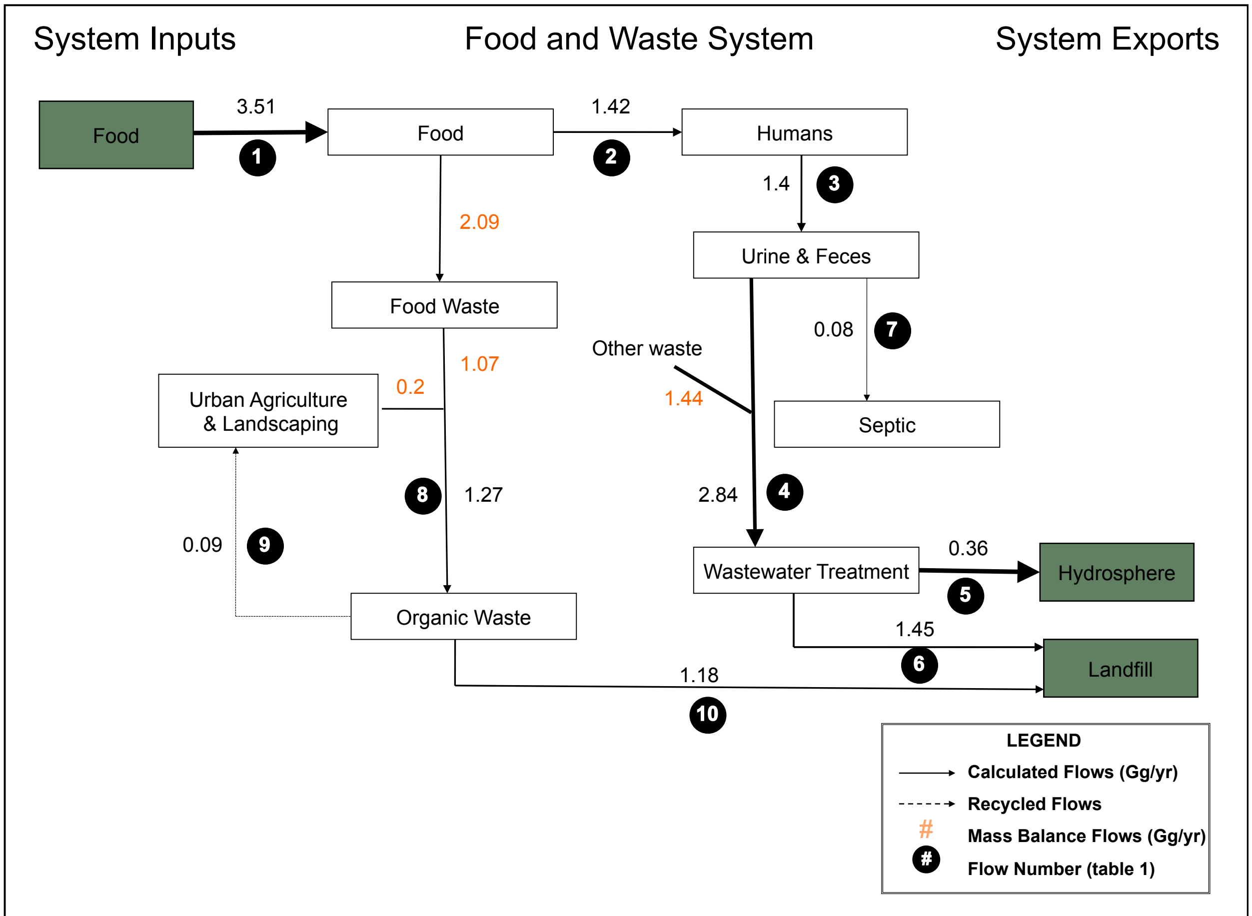


Figure 3.2 Phosphorus flows in the food system on the island of Montreal in gigagrams of P yr^{-1} where the size of arrows represents the magnitude of flows. Recycled flows are represented by dashed arrows, and flows calculated by mass balance (subtracting or adding calculated flows) are shown in orange. Green boxes represent inputs and exports to and from the island. Numbers in black circles represent the flow identification number, which is associated with a description of the flow and calculation methods in Table 3.1.

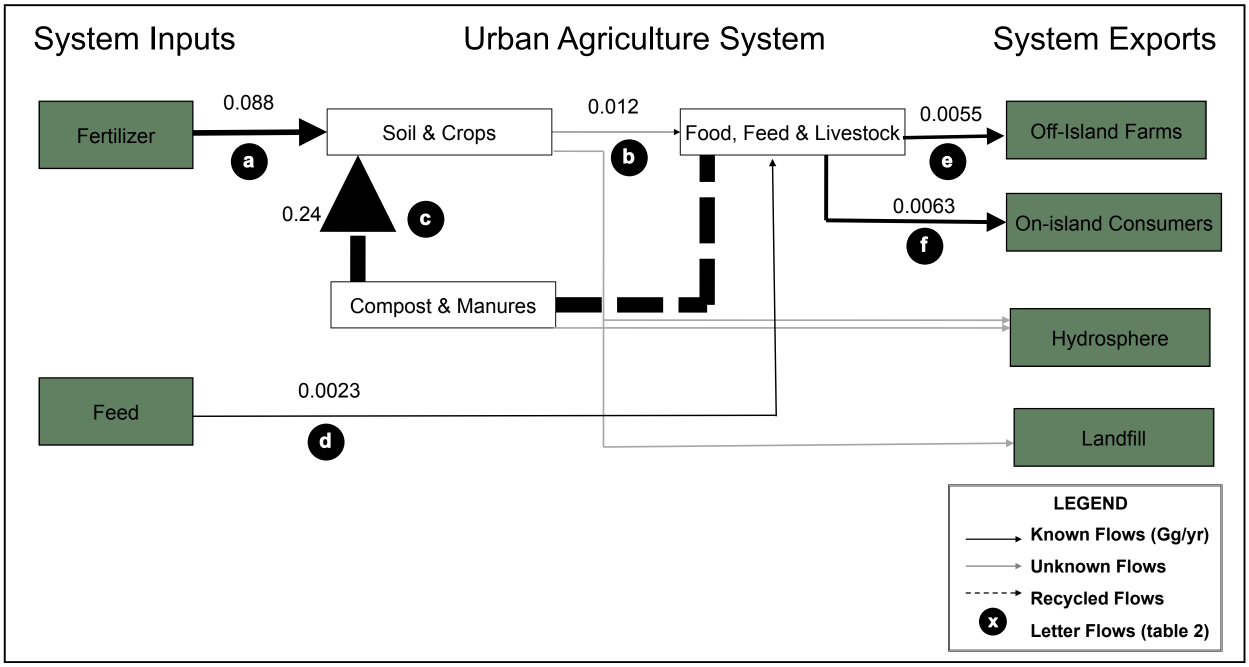


Figure 3.3 Phosphorus flows in the urban agriculture (UA) system on the island of Montreal in gigagrams of P yr^{-1} where the size of arrows represents the magnitude of flows. Recycled flows are represented by dashed arrows, and unknown flows (i.e., runoff and erosion to the waterways, and amount of organic material from UA sent to landfill) are represented by grey arrows. Green boxes represent inputs and exports to and from the UA system. Letters in black circles represent the flow identification letters, which are associated with a description of the flow and calculation methods in Table 3.2.

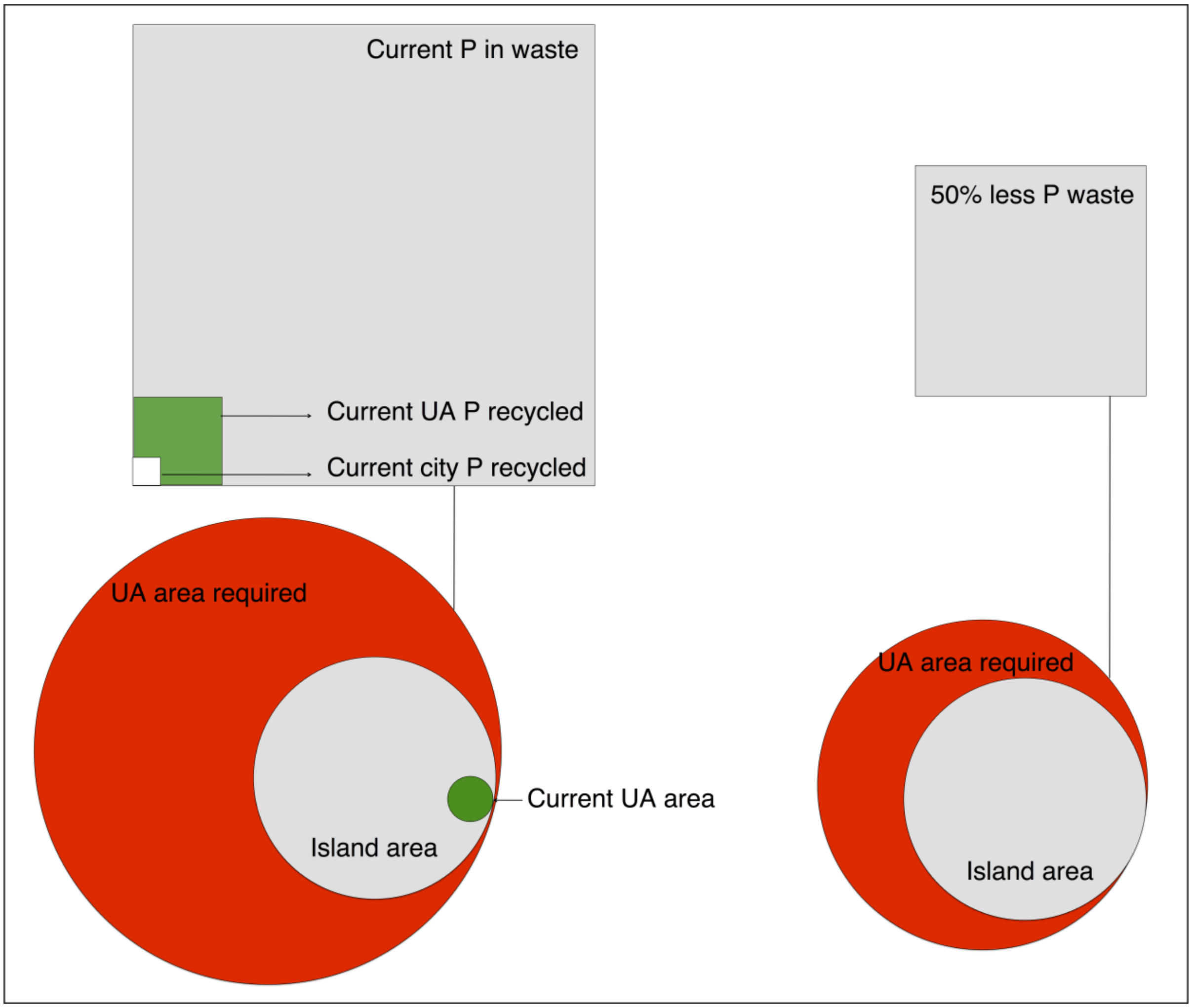


Figure 3.4 Current and potential future role of urban agriculture (UA) in Montreal P cycling. Two scenarios are visually represented in terms of the amount of P waste produced, recycled, and the amount of corresponding land in UA production required. The reference current state is represented by the grey square on the top left, which is the amount of P in organic waste produced on the island of Montreal. The small white square represents the proportional amount of the P wasted that is currently recycled, the green square, also proportional in size to current P-waste production, represents the estimated amount of P recycled through UA. The grey circle represents Montreal island area, and the green circle the proportional area of the island under UA production. Scenario one, on the left-hand side illustrates the area of UA necessary to recycle all P waste produced as the red circle (317% bigger than the island) if P application is equal to P harvest and all P application is from recycled sources. Scenario two, on the right-hand side, illustrates the area of UA required as the red circle (186% bigger than the island) if Montreal produces 50% less P waste. P waste in these scenarios exclude P in sewage waste.

Table 3.1 Data sources for Montreal food system P budget. We did not include runoff and erosion losses, or P lost in storm events due to wastewater treatment plant limited capacity because of a lack of data.

Flow number (in Figure 3.2)	**Flow name**	**Equation**
1	**P imports in Food**	(Food supply* P concentration of food* population) – (percentage pre-market food wasted* food supply* P concentration of food*population)+ (2*Restaurant and industry organic waste)
		Data sources
		Food supply: FAO (2013) in kg person^{-1}yr^{-1} P concentration of food: USDA (2009), Ministry of Education (2010) Population: Satistics Canada (2013) Pre-market food waste: Gustavsson et al. (2011), Gooch et al. (2010) in % Restaurant and industry organic waste: Solinov (2012), Fortin et al. (2011)
		Assumptions and specifications
		Food imports were based on Montreal's total population in 2012 and FAO average Canadian diet, both in terms of content and quantities. FAO reports diet in quantities grown, not eaten, thus quantities were transformed based on average North American food waste percentages before reaching retail stores. Because this was based on resident population, we added the food entering the system through restaurants and industry. We had information on organic waste produced by restaurants and industry, and the percentage of food wasted, but not food imports. As such we back-calculated food imported by using the percentage wasted (50%) and the amount. We only included food entering the city for consumption and ignored food products that transit through the city to be exported elsewhere, and as such we are looking at the net import and export of P in the Montreal food system.
2	**Food P consumption**	**Equation**
		P imports in food (Flow 1) – (Post-market food waste * P concentration of food waste)
		Data sources

		Post-market food waste: Gustavsson et al. (2011), Gooch et al. (2010) in % P concentration of food items: USDA (2009), Ministry of Education (2010)
		Assumptions and specifications
		Food consumption was calculated by subtracting the estimated amount of food wasted before it is consumed (thus including waste at stores and at home) from the food entering the island.
3	**P excreted**	**Equation**
		Flow 2 * percentage excreted
		Data sources
		Percentage of P excreted by humans: Drangert (1998)
4	**P entering wastewater treatment plant (WWTP)**	**Equation**
		(Water entering plant * P concentration in water entering) + (biosoilds to landfill * P concentration of biosolids)
		Data sources
		Volume of water entering plant: Pilote (2011) in m^3 yr^{-1} P concentration in water entering: Pilote (2011) in mg of P l^{-1} Biosolids to landfill: Pilote (2011) in dry matter (DM) tons yr^{-1} P concentration of biosolids: Personal communication with sewage treatment plant expressed in $\%P^2O^5$ DM
		Assumptions and specifications
		Montreal has only one wastewater treatment plant on the island. The quantity of water and P concentration of that incoming water, as well as the amount of biosolids collected by the plant and their P concentration were used to calculate the total P entering the plant.
5	**P leaving WWTP to water**	**Equation**
		Water leaving plant * P concentration in water leaving
		Data sources
		Volume of water leaving plant: Pilote (2011) in m^3 yr^{-1} P concentration in water leaving:

		Pilote (2011) in mg of P l^{-1}
		Assumptions and specifications
		The quantity of water and P concentration of that outgoing water from the plant were available through official reports and used to calculate the total P leaving the plant.
6	**Biosolids P entering landfill**	**Equation**
		Biosoilds to landfill * P concentration of biosolids
		Data sources
		Biosolids to landfill: Pilote (2011) in dry matter (DM) tons yr^{-1} P concentration of biosolids: Personal communication with sewage treatment plant expressed in $\%P^2O^5$ DM
		Assumptions and specifications
		The treatment plant currently incinerates all biosolid waste and sends it to landfill, and we used the amount of biosolid ash and its concentration in P to calculate the total P going to landfill. However, we did not include P that may be found in the sands used in the water treatment process at the plant and subsequently landfilled or P in the large residues collected at the plant because of lack of data.
7	**P entering soils through septic system**	**Equation**
		Boisolids produced in septic system * P concentration of biosolids
		Data sources
		Biosolids produced in septic system: Communauté métropolitaine de Montréal (CMM) (2002) in tons yr^{-1} P concentration of biosolids: Perron and Hébert (2007) in $\%P^2O^5$ in DM
		Assumptions and specifications
		Although most of the island is connected to the WWTP, there still are some septic systems. We used official government data on the amount of biosolids produced by septic systems on the island in 2001, thus assuming that any population growth on the island happened in areas connected to the WWTP. We used a biosolid P concentration reported for average municipal sewage waste because a concentration was not available for septic systems in the province of Quebec.
8	**Organic waste (food and green waste) P produced**	**Equation**
		(Residential organic waste recycled * inverse of percentage of organic waste recycled* proportion of organic waste that is food* food waste composition*P concentration in food waste) +(Residential organic waste recycled * inverse of percentage of organic waste recycled* proportion of organic waste that is green* P concentration in green waste) + (Business organic waste * P concentration of food waste)
		Data sources
		Residential organic waste recycled and population served: Ville de Montreal (2013a) in kg $person^{-1}$ yr^{-1} and % of total organic waste recycled

		Buisness organic waste precycled: Fortin et al. (2011) Food waste composition: Satistics Canada (2009) in % P concentration in food: International Fertilizer Industry Association et al. (2002), USDA (2009), Ministry of Education (2010) P content in green waste: FAO (2004), Cogger (2014) Buisness organic waste produced: Solinov (2012) in tons yr^{-1}
		Assumptions and specifications
		We calculated the amount of P in organic waste (food waste, green landscaping waste, and wood) generated on the island by using official government estimates of organic waste recycled by residents, businesses, and institutions, and back-calculating to the total waste produced based on the percentages recycled. Proportion of organic waste that was food versus green waste was determined through communication with the City waste department, based on their internal data We included green and wood waste even though they are not strictly part of the food system as they are used in most compost and thus tested P contents reflect the inclusion of such waste products. We used P contents for fruits and vegetables (for food), green waste, and wood according to their proportional make-up of waste. The P concentrations include the conversion to dry weight.
9	**Organic waste P recycled**	**Equation**
		(Residential organic waste recycled * proportion of organic waste that is food* P concentration in food) +(Residential organic waste recycled* proportion of organic waste that is green* P concentration in green waste) + (Business organic waste recycled * P concentration of food)
		Data sources
		Organic waste recycled and population served: Ville de Montreal (2013a) in kg $person^{-1}$ yr^{-1} and % of total organic waste recycled Buisness organic waste recycled: Fortin et al. (2011) P concentration in food: International Fertilizer Industry Association et al. (2002), USDA (2009) P content in green waste: FAO (2004), Cogger (2014)

		Assumptions and specifications
		We calculated the amount recycled through composting using both official government figures of organic waste currently recycled through households (11%) and adding the amount of organic waste recycled of businesses known to compost. Here we use the average fruit and vegetable P concentration instead of weighting by Canadian food waste make-up because the city doesn't currently compost high amounts of meats and processed foods.
10	**Organic waste P landfilled**	**Equation**
		Flow 8- Flow 9

Table 3.2 Description of flow calculations for urban agriculture (UA) P budget. Data are from surveys, and if P content was not provided by the survey respondent the values in Table 3.3 were used. Note that we did not include flows relating to runoff and erosion losses or inputs from soil and soil mixes if P content was not available from the survey respondent (e.g., soil, potting-mix, vermiculite, perlite, or coco fiber).

Flow letter (in Figure 3.3)	**Flow name**	**Equation**	**Assumptions and Specifications**
a	P fertilizer and soil amendments imported applied soil	Sum for all gardens in type n [(total P inputs from off-island source/ area of garden)*(area of garden/total area of UA type n surveyed)] estimated area for type n	Weighted P application by area of farm or garden, and by the estimated area for the 3 types of management, so type n is type of management (see x, y, z) See Table 3.3 for types of inputs considered
b	P in harvested crops (feed and food)	Sum for all gardens in type n [(total P harvested/ area of garden)*(area of garden/total area of UA type n surveyed)] *estimated area for type n	Weighted P application by area of farm or garden, and by the estimated area for the 3 types of management, so type n is type of management (see x, y, z)
c	P compost and manure from on-island sources applied to soil	Sum for all gardens in type n [(total P inputs from on-island sources/ area of garden)*(area of garden/total area of UA type n surveyed)] *estimated area for type n	Weighted P application by area of farm or garden, and by the estimated area for the 3 types of management, so type n is type of management (see x, y, z) We combined recycled inputs (plant residues, compost, vermicompost, and animal manures) into one flow in order to maintain anonymity of survey respondents
d	P imported as animal feed and supplements	Sum for all types [(Feed or supplement imported type n*P concentration type n)]	Did not scale to estimated area of UA because we surveyed all known farms that raise animals and P concentrations were obtained by survey respondents or by manufacturers
e	P exported off island (food, feed, and manure)	P as exported manure + P as exported feed	Did not scale to estimated area of UA because we surveyed all known farms that export
f	P consumed by on-island residents	(P harvested – P harvested for animal feed) + P in animal products (milk and eggs)	P harvested is scaled to total UA area but P in animal feed and P in animal products are not because we surveyed all known farms that raise animals
x	** Estimating total area: UA private and community garden type	(% of households practicing UA* % of practicing households doing UA in back-, side-, front-yard *# of households on island * average size of vegetable garden)+ (% of households practicing UA* % of	References: Household participating in UA: Ville de Montréal (2013b)

Flow letter (in Figure 3.3)	Flow name	Equation	Assumptions and Specifications
		practicing households doing UA on roof or balcony*# of households on island * area of 4 alternatives containers (0.96m^2))+ (area of community gardens)	Area of private backyard gardens: Butterfield (2009) Community garden area: Office de consultation publique de Montréal (2012)
y	Estimating total area: UA collective garden type	(Area surveyed collective gardens)+(area of missing collective gardens with known area)+(average area of known collective gardens reporting area*# of collective gardens with unknown area)	Reference: Area of collective gardens not surveyed: CRAPAUD et al. (2013)
z	Estimating total area: UA farm type	Known area of farms from survey + reported area of the 2 farms we did not survey	Reference: Area of farms not surveyed: CRAPAUD et al. (2013)

Table 3.3 Numbers used to calculate P inputs when not available with information directly from survey.

Inputs	Specification	Bulk density	Dry Matter	P content	Data sources, assumptions, and specifications
Vermicompost		600 kg $m^{3\ -1}$		0.0115 P conversion	Singh et al. (2013)
Shrimp and/or crab compost (or other marine based compost)		0.41507 kg l^{-1}		0.75% P_2O_5	Average based on the commercial fertilizers found in Montreal hardware and garden stores that had information on density or P content
Bio-forest compost		.41666 kg l^{-1}		0.8% P_2O_5	Used numbers on Fafard company bio-forest compost bags found in stores
Plant-based compost (green and table waste)		533.8783 $kgm^{3\ -1}$	30%	1%P	Bulk density is average of "good compost" according to (The US Composting Council 2001), home compost west island (Adhikari et al. 2012) for DM and P content because they are specific to Montreal. Compost bulk density varies from 700-1,200 pounds per cubic yard, and desirable is consider 800-1000 pounds per cubic yard
Sheep/goat manure	non-composted		28%	4lbs P_2O_5 ton^{-1}	Rosen and Bierman (2005)
	composted	0.417 kg l^{-1}		0.4% P_2O_5	Used numbers on Signature master gardener brand bags found in stores
Cow/beef manure	composted	12.5 kg bag^{-1} (assume its 30l bag but that is not explicitly stated)		0.4% P_2O_5	Used average of values for brands found in store
Chicken manure (including quail)	litter	546.5 kg $m^{3\ -1}$		1.538% P	Tiquia and Tam (2002)
	composted	10 kg 30l bag^{-1}		3% P_2O_5	Used numbers on Actisol brand bags found in stores
Horse manure	non-composted		46%	4 lbs ton^{-1}	Rosen and Bierman (2005)

Inputs	Specification	Bulk density	Dry Matter	P content	Data sources, assumptions, and specifications
	composted	NA	45%	0.3% P_2O_5	Used numbers on Solabiol brand (found online December 2013 http://www.solabiol.com/nos-solutions/planter/les-amendements-pour-fertiliser/fumier-de-cheval)
Pig manure	liquid	1 kg l^{-1}		0.9kg $1000l^{-1}$	Saskatchewan Agriculture and Food , The Prairie Province's Committee on Livestock Development and Manure Management Report
Liquid fertilizer		1 kg l^{-1}			Assumed density of water
Bone meal		1 kg l^{-1}		10% P_2O_5	Commercial inputs found in stores didn't report both density and P content so assuming 1 to 1 ratio (and online values very but are close), P concentration is average of what was reported in stores
Shrimp and/or crab meal (or other marine based meal)				3.5% P_2O_5	Used numbers on Bionord brand bags found in stores
Fish emulsion		1 kg l^{-1}		4% P_2O_5	Used numbers on Acadie brand bottles found in stores and assuming density of water
Marine algae		1.0007 g ml^{-1}		1.5% P_2O_5	Used the average of brands found in stores
Straw		150 kg $m^{3\ -1}$	88%	0.08375% P (DM basis)	Density if for a little rectangle bail in Quebec with medium packing in (Savoie et al. 2002), DM is average of straws listed in (Redden 2012), P content is an average of (Redden 2012), (White et al. 1981), (Anderson and Hoffman 2006)
Hay		150 kg $m^{3\ -1}$	0.4209	0.2987% P	
Wood chips				0	Assuming 0 for hard dry woods (see BRF for younger wood)
Leaves		163.15 kg $m^{3\ -1}$	39%	0.1015% P	Middle point between high valued of uncompacted leaves and low point of compacted leaves according to: (US Environmental Protection Agency (EPA)),for DM (Cogger et al. 2002) P value is middle point of the leaf litter values found in (Côté and Fyles 1994) (used this number over yard waste because dead leaves don't contain as much as fresh ones)
Rameal frangmented wood (BRF)		492 kg $m^{3\ -1}$ (fresh density)	65.35%	0.26 % P_2O_5 (DM basis)	Godden et al. (2007)
Lawn and yard waste		577.257487kg $m^{3\ -1}$		0.3% P	Density (Cogger 2014), P content (FAO 2004)

Inputs	Specification	Bulk density	Dry Matter	P content	Data sources, assumptions, and specifications
Grass				0.3% P	P content (FAO 2004)
Potting mix and fertilized potting mix (e.g. miracle grow mix)				0	Because P in soil and potting mixes is not systematically reported, we did not include them in P inputs except when site-specific information was available. We did however include the use of soils in our count of types of inputs used.
Black soil		0.291 kg l^{-1}		0	Non-weighted average of all soils that were commercially available and had both weight and volume on the bag
Peat				0	University of Maryland Extension (2013)
Perlite				0	University of Maryland Extension (2013)
Vermiculite				0	University of Maryland Extension (2013)
Coco fibers				0	University of Maryland Extension (2013)
Crop yield		0.643 kg $m^{3\ -1}$		0.0003 P and DM conversion	Weighted average of yields in Montreal gardens by area (Duchemin et al. 2009), and New York city community gardens with tomatoes (Ackerman 2011), P content is average of fruits and vegetables as used in (Metson et al. 2012). See SI figure one for more detail on yield assumptions

Table 3.4 Summary of urban agriculture (UA) characteristics by managing organization and substrate type.

Type of social organization managing UA			
Type	**Number of respondents**	**Total area surveyed in km^2** (% of total)	**Total area estimated to be cultivated on the island in km^2** (% total)
Community and personal gardens	83	0.001 (0.04%)	13.9 (77.34)
Collective, school, business, and institution gardens	50	0.02 (0.74%)	0.03 (0.15)
Commercial farms (and large university farms)	10	3.10 (99.21%)	4.05 (22.5)
Total	143 (665 gardens)	3.12	18.00
Substrate type in UA			
Type	**Number of respondents**	**Total area surveyed in km^2**	**n/a**
Soil (on the ground)	89	3.1	
Both soil and container	28	0.002	
Containers and roof top	26	0.008	

3.9 Supplemental Information

3.9.1 Methods

We used survey and literature review methods to quantify P flows through the UA system on the island of Montreal. These were the most appropriate methods considering the temporal, spatial, and system scope of the research questions, i.e., we required data about all types of UA, over the whole island, for one year. As such, an in depth coverage of a few gardens or extensive primary sampling of biophysical parameters, although interesting, would not have been appropriate. We could not have collected adequate and representative data on soil P content, quantity and P content of inputs, crop harvests, composting, and losses through runoff or erosion over one season because of the high probability of large variation between different farms and gardens on such a heterogeneous urban landscape (Wortman and Lovell 2013). Our survey sampling strategy should reflect some of the variability in practices even though we could not collect primary data on P flows in the UA system.

Survey administration

The survey consisted of eight questions with four additional questions for animal production when it was relevant to the respondent. The survey used 2012 as a reference year for larger gardens and farms that kept records. If records did not exist for 2012, which was the case for most small and private gardeners, we used 2013 as a reference in order to ask respondents to collect information throughout the season when it was possible and thus minimize recall error. When ever possible, surveys were conducted in the garden or in the office where quantitative data may be stored. We measured the area of gardens ourselves when the respondent did not have such records. We counted the number of bags or containers of different types of inputs and noted the weight and NPK ratio of all inputs when it was accessible and the respondent did not have records. We also asked for copies of any supporting documentation. All survey data were entered and stored in through Limesurvey online system (LimeSurvey Project Team and Schmitz 2012), and was done with McGill Research Ethical Board approval (REB File#: 995-0213).

Following are the specific research questions asked:

1. Indicate the beginning of the growing season (first time plants are planted) and the end of the growing season (last harvest) in the garden (s) with an "x".

Month	Week 1	Week 2	Week 3	Week 4
January				
February				
Mach				
April				
May				
June				
July				
August				
September				
October				
November				
December				

2. How much area does each of the following types of gardens does your organization/institution/company manages?

	Area	**Measurement unit a) square meters; b) square feet; c) acres; d) % of garden(s); e) other (specify)**	**Additional information**
Total area (all types of gardens together)			
In soil (directly in Montreal earth or in raised beds)			
In containers (includes all pots, smart pots, biotops, and any other container that is of a "movable size")			
On roof (gardens directly on the roof with a member and NOT in containers)			
Hydroponics (without soil)			
Other (specify)			

* We define containers as an object that can easily be moved

	Mark the inputs	**How much input**	**Measurement unit a) kilogram; b)**	**Where did the inputs come from 1) on-site; 2)**	**What is the N :P :K***	**Additional information**

	that you use with an "x" .	did you use?	pounds; c) tonnes; d) meter cubed; e) liter; f) gallon; g) cubic yard	Neighbor/friend; 3) Store; 4) Farmer or producer located on the island; 5) Municipality; 6) Other (specify)	ratio (if you know it)?	
Potting mix						
Fertilized potting mix (e.g. miracle grow mix)						
Black soil						
Clay-based soil						
Peat						
Perlite						
Vermiculite						
Coco fibers						
Other soil/substrate used (specify)						
Vermicompost						
Shrimp and/or crab compost (or other marine based compost)						
Bio-forest compost						
Plant-based compost (green and table waste)						
Other compost types used (specify)						
Sheep/goat manure						
Cow/beef manure						
Chicken manure						

Horse manure						
Mixed source manure						
Other manure types used (specify)						
Solid fertilizer						
Liquid fertilizer						
Bone meal						
Shrimp and/or crab meal (or other marine based meal)						
Fish emulsion						
Marine algae						
Other fertilizer types used (specify)						
Straw						
Hay						
Wood chips						
Leaves						
Non-organic materials						
Other mulch types used (specify)						

3. What percentage of the total space of the garden is used for food production? This **includes**: planted area, alleys to move around, and orchards. It does **not include**: play and other recreational areas, grassy areas, compost production area, or storage area.

	%

4. What is the number and size of the containers used if you use containers to garden?

Type of container	**Number of containers**	**Approximate size of the container**	**Measurement unit** **a) meters cubed**	**Additional information**

			b) liter **c) gallon**	
Double-bottom from Alternatives				
Double-botton made at home				
Biotop				
Rootpouch				
Smartpot				
Home-made bag				
Plastic container (without water reservoir)				
Other (specify)				

Note: Biotop containers are about 30 liters, the Smartpot containers vary between 4 and 760 liters, the double-bottoms from Alternatives are about 70 liters, the Rootpouch bags vary between 3.8 and 2271liters.

QUESTIONS ABOUT INPUTS

5. The following table will allow you to answer the following three questions:

a) What are the inputs (soil and other substrates, compost, manure, fertilizer, and mulch) you used in the reference season you indicated at the beginning of the survey?

b) How much of each input did you use for the total area of all gardens in the same reference year?

c) Where did you get these inputs?

Note: Only fill out the sections that match your gardening practices.

*N:P:K is the ratio of nitrogen, phosphorus and potassium in your fertilizer or compost. This number is often written on the bag, or it is possible that you have done chemical analyses in lab on your compost or soil and thus know this ratio.

6. a) Do you use the following methods to get rid of your organic residues?

	Yes	**No**	**Additional information**
Composting your-self*			
Left on soil			
Municipal collection of green and food waste (to be composted)			
Private company collection of green and food waste (to be composted)			
Landfill			
Other (specify)			

*Production of compost your-self includes: compost produced in a compost on-site or off-site with a partner on the island of Montreal. It can include garden waste, food waste, and high carbon materials like wood, leaves, cardboard and paper.

6. b) If you compost, how much compost do you produce?

	Quantity in a year	**Measurement unit** **a) kilogram;** **b) pound;** **c) cubic meter;** **d) liter;** **e) gallon;** **f) cubic yard**	**Additional information**
Compost production			

QUESTIONS ON FOOD PRODUCTION AND CONSUMPTION

7. a) Do you measure food production (harvest) in your garden(s)?

Yes	**No**	**Additional information**

7. b) How much did you harvest during the reference year?

	Quantity harvested over the year	**Measurement unit** **a) kilogram;** **b) pound;** **c) meter cubed;** **d) liter;** **e) gallon;**	**Additional information**
Total			

	Mark all the groups that consume the fruits and vegetables harvested in your garden(s) with an "x".	**Quantity**	**Measurement unit** **a) kilogram;** **b) pound;** **c) meter cubed;** **d) liter;** **e) gallon;** **f) % of harvest**
Gardener(s) and their family and friends			
Food bank			
Employees (of your company)			

Clients			
Other (specify)			

8. a) Who consumes the fruits and vegetables produced in your garden(s) and in and in what quantity or proportion?

8. b) If you sell all or part of **your (or your organization's) harvest**, how to distribute it to your clients?

If you have clients….	**Mark all the distribution circuits you use with an "x"**	**Quantity**	**Measurement unit** **a) kilogram** **b) pound** **c) meter cubed** **d) liter** **e) gallon** **f) % of harvest**	**Additional information**
Community supported agriculture baskets (CSA)				
On-farm (garden) sale				
Public market				
Grocery store (through a whole saler)				
Grocery store (directly)				
Restaurants				
Other (specify)				

ADDITIONAL INFORMATION

If you have any additional information, comments, or suggestions about this survey please share them with us here. Also, if you know other urban agriculture actors (participants) that you believe would be relevant to this research (and this survey) please indicate them here.

Available inputs to gardeners and possible yields in Montreal

We visited the largest garden retailers on the island (in person and online) to document all inputs containing P (their dimensions, weight, and P content) in order to give picture examples to survey respondents, and also to create average densities and P concentrations to inputs when not provided by the survey taker. We did not include soil if survey respondents did not have weight and P content information on-hand. Companies are not required to measure or report P content for soil blends by law and thus, more often than not, do not measure P content. We did not include losses through runoff and erosion, proportion of harvest that might be grown but eaten by animals in our system, or any primary data on biophysical measures. We combined recycled inputs (plant residues, compost, vermicompost, and animal manures) into one flow in order to maintain anonymity of survey respondents.

We used a conservative yield estimate as to not over estimate the amount of P harvested. When yield data was not available through our survey, we estimated yield based on data obtained in gardens in Montreal and New York City. We compared our estimated yield to other studies about UA and our own survey yield data to ensure our estimate was reasonable (SI Figure 1). Studies using data from many countries support the claim that smaller plots in rural areas can achieve higher yields than larger agricultural fields (Cornia 1985, Barrett et al. 2010), as such yields for biodiverse production in small plots in urban areas can be assumed to be high (although yields may vary because of regional local biophysical conditions and management practices).

Comparison within the UA subsystem

We described UA practices by the type of actor managing production (farms, collective gardens, and private gardens), and type of substrate used (soil, mixed, or alternative (i.e., containers and roofs). We assessed if the P balances (in g of P per m^2) were different, and if the percentage of P from on-island recycled sources was different between management groups and by substrate use. These comparisons were based on survey responses, and we expressed values for each category both as means weighted by each respondents cultivated area and as unweighted means where each respondent in a group having equal importance, in order to run statistical analysis. We removed respondents in the “farms” category when analyzing the relationship between substrate type and P balances and recycling practices. We used Kruskal-Wallis analysis of variance (in R, R Development Core Team (2011)) test the unweighted means because data were not distributed normally.

3.9.2 Results and Discussion

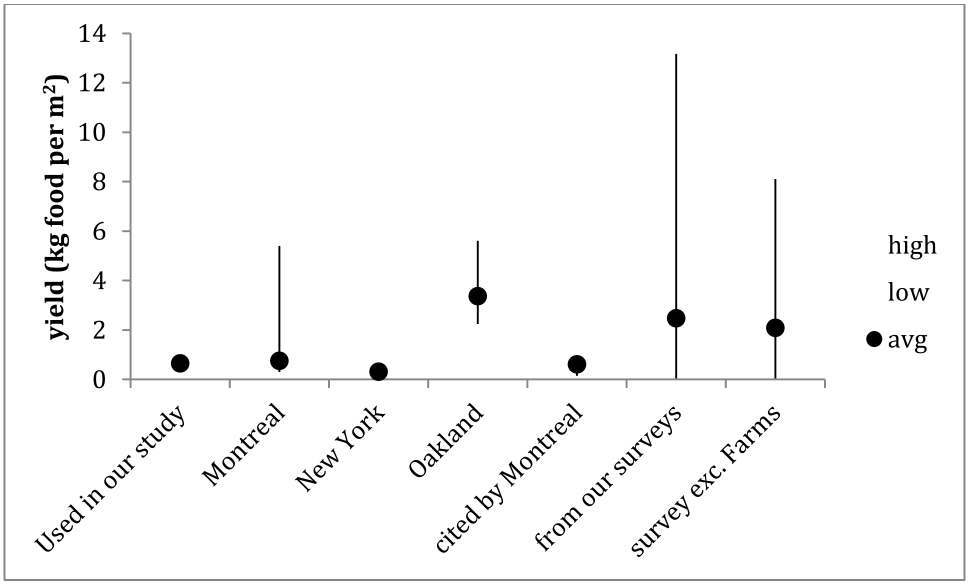
Comparison within the UA subsystem

The P harvested through crops was higher than P applied to soil over the area cultivated by the 11 farms surveyed (-0.84 g of P per m^2, SI Figure 2 and SI Table 1). However, when each farm was considered equality (i.e., not weighted by respondents' area cultivated) the mean application rate of P was higher than the mean P in harvested material, resulting in a positive P balance of 15.3 g of P per m^2. All farms practiced some kind of P recycling strategy (compost or leaving residues on soil) and 80% of P applied to soils was from on-island recycled sources, including manure reuse (cow manure accounted for 39% of P applied). Respondents used an average of 5.4 inputs, and the input used most often was potting mix (60% of respondents). While collective, community, and private gardeners largely applied more P than harvested, farms had more variable P balances. Some farms applied less P than was harvested in crops, adhering to application rates based on soil tests and the Quebec ministry of agriculture, fisheries, and food regulations to ensure P balance on farms. These farms mostly use recycled P from manure. Some farms however applied more P than harvested in 2012. For example, one farm was "building" soil by applying Rameal fragmented wood. Increases in UA area through large farms would likely follow provincial P application guidelines, limiting pollution risk.

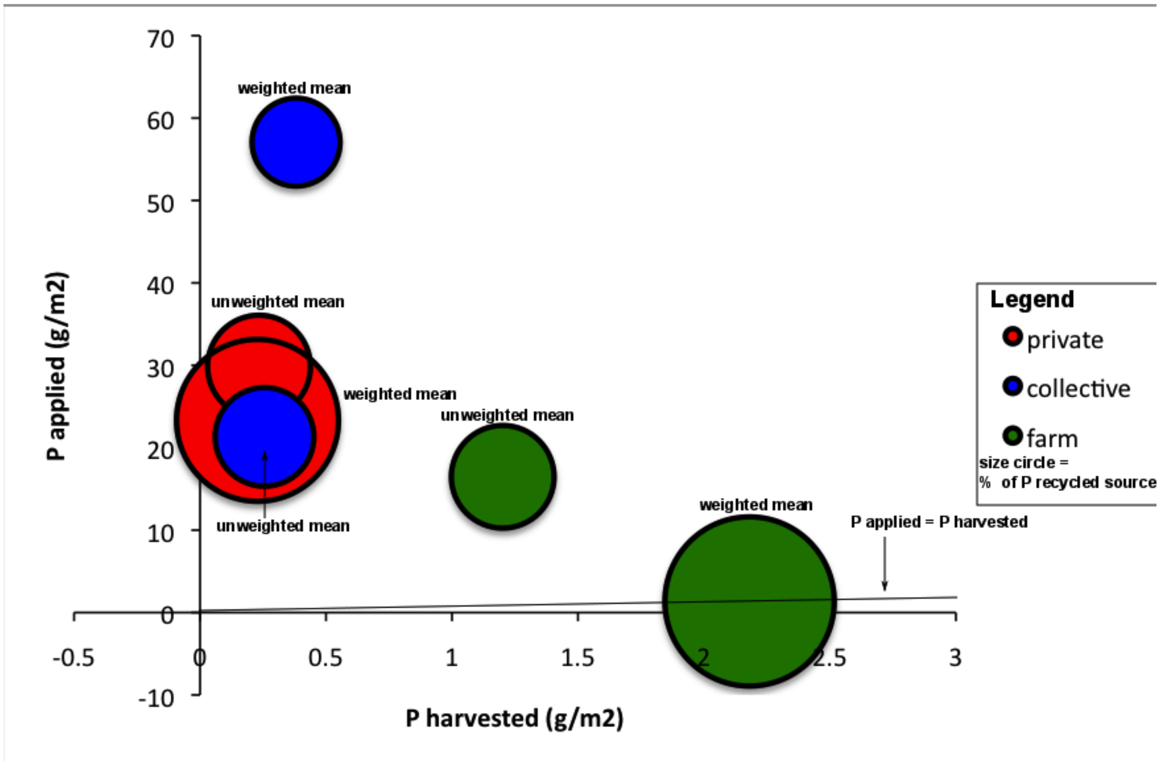
The area cultivated by collective gardens had a positive P balance (applied > harvested) of 21.1 g P per m^2 and a greater positive P balance when collective gardens we not weighted by area (mean of 56.7 g of P per m^2, SI Figure 2 and SI Table 1). Based on the 50 survey respondents, plant-based compost was the input that contributed the most to the total P applied to gardens (35%) and most used by respondents (56% of respondents used compost). On average collective gardens used 5 different inputs. Although 84% of respondents practiced composting (or left organic residues on soil), only 27% of P applied to collective gardens was from an on-island recycled source.

Community and private gardens had similar positive P balance to the community gardens, where 23.0 g of P per m^2 was applied (SI Figure 2 and SI Table 1). The P balance was slightly higher for the unweighted mean of the 83 respondents (29.6 g of P per m^2). As in the collective gardens, plant-based compost was the input that most contributed to P inputs (72%) and was the most widely used (34% of respondents). Respondents from community and private gardens used on average 2 inputs in their gardens. The majority of respondents composted or left residues on soil, and 73% of P applied to soil was from a recycled on-island source.

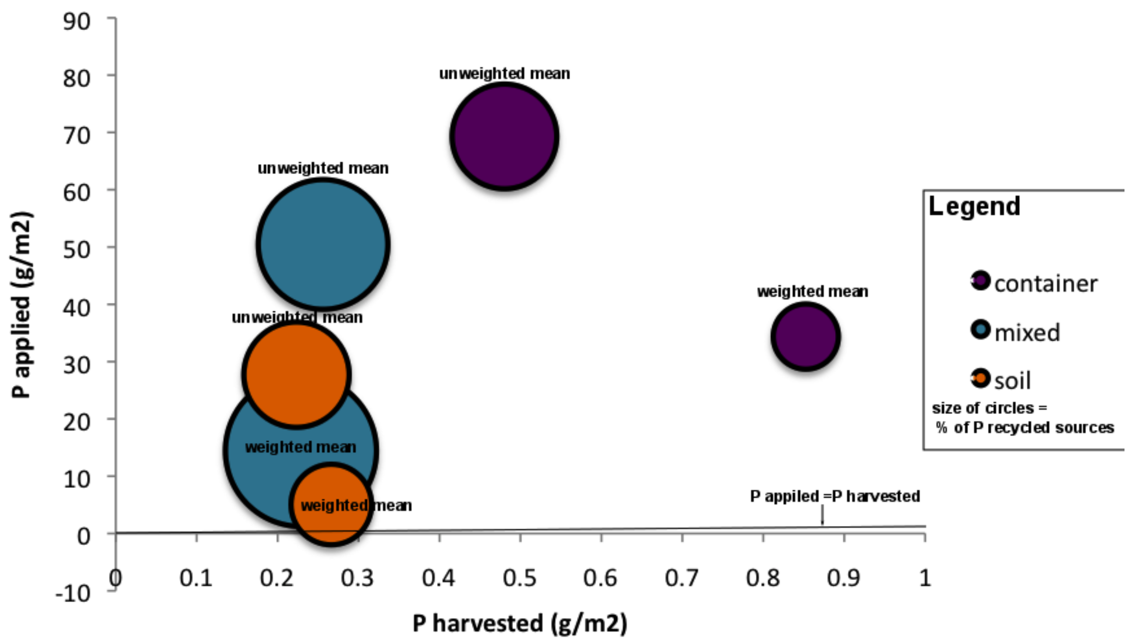
In addition to types of UA, P cycling and nutrient management practices differed among substrate types used by survey respondents. Here we only compare the use of substrate types from respondents in the collective, and the private and community garden types because those two categories have the largest estimated area under cultivation (Table 3.3) and because large farms mostly cultivated on soil and are subject to regulations that make them quite distinct from the other two groups. P balances (unweighted) of respondents who used mixed (50.2 g of P per m^2) or exclusively alternative substrates (60.8 g of P per m^2) were higher than those cultivating only in soil (26.7 g of P per m^2, mean rank statistically significant at p-value of 0.0805). In all cases P applied exceeded P harvested (SI Figure 6 and SI Table 5). The weighted P balance of respondents who cultivated both in soil and in alternative substrates applied less excess P than those cultivating exclusively in soil or alternative substrates (14.2g of P per m^2 compared to 35.7 and 33.5 g of P per m^2). Marine-based compost was the most frequently used input by respondents cultivating in alternative substrate (48% of respondents), and contributed most to total P applied. Mixed and exclusively soil cultivation respondents used plant-based compost most frequently and as their most important source of P, contributing 31% of P in soil gardens and 70% of P in mixed gardens. The majority of all respondents practiced composting or left residues on soil, although mixed substrate users had the highest percentage of respondents practicing these P recycling strategies (96%).



SI Figure 1. Average and range (high and low) of yields reported in UA studies compared to our study. In this study we used a weighted average (by area) of data reported in Duchemin et al. (2009) and the highest reported value in in Ackerman (2011) (because it included tomatoes and mixed vegetables). Montreal reported yields came from 8 gardeners (38 gardens, Duchemin et al. (2009)), New York yields reported in Ackerman (2011) came from data in community gardens and urban farms, and Oakland California yields are from McClintock et al. (2013) estimating possible yields based on conventional agriculture yields and low and medium biointensive cultures. "From our surveys" are the average, maximum, and minimum values for the 37 respondents that had yield data, nine of which were farms. And the "survey exc. Farms" represents the average, maximum and minimum values in the collective, private and community gardens we surveyed.



SI Figure 2. Summary of P applied, P harvested, and P recycled by type of UA management in Montreal. The size of circles represent the percentage of P inputs that are from on-island recycled sources. The black 1:1 line represents P balance where P input per m^2 cultivated equals the P from harvested crops per m^2. If a bubble is above the line then P inputs are larger than P harvested (a positive P balance), and if the bubble is below the line then P inputs are smaller than P harvested (a negative P balance). For each management type (i.e., private and community gardens (red), collective gardens (blue), and larger farms (green)) we show both the unweighted mean of survey respondents and the weighted mean by area cultivated.



SI Figure 3. Summary of P applied, P harvested, and P recycled by substrate type excluding large farms. The size of circles represents the percentage of P inputs that are from on-island recycled sources. The black 1:1 line represents P balance where P input per m^2 cultivated equals P from harvested crops per m^2. If a bubble is above the line then P inputs are larger than P harvested (a positive P balance), and if it is below the line then P inputs are smaller than P harvested (a negative P balance). For each substrate type (i.e., container and roof-top substrate (purple), mixed container and soil substrate in the same garden (aqua), and directly in soil (orange-yellow)), we show both the unweighted mean of survey respondents and the weighted mean by area cultivated.

SI Table 1. Summary of managing organizations input use, waste management, and P balance. Weighted means are the total value of the management type where each survey response has been weighted by area cultivated. When not indicated as weighted, means are not weighted by area, thus each survey holds the same importance.

Management value	**All farms and gardens**	**Collective, school, business, and institution gardens**	**Community and personal gardens**	**Commercial farms (and large university farms)**
Weighted P balance (g of P/m^2)	-0.66	21.06	23.04	-0.84
Mean P balance (g of P/m^2)	38.27	56.7	29.61	15.27
Weighted % of P from on-island recycled sources	74	27	73	80
Mean % of P from on-island recycled sources	26	21	30	30
Mean number of inputs used	3.5	5.1	2.3	5.4
Input type most used (% of respondents)	Plant-based compost (42)	Plant-based compost (56)	Plant-based compost (34)	Potting Mix (60)
Weighted input contributing to P input most (% of total inputs)	Cow manure (36)	Plant-based compost (35)	Plant-based compost (72)	Cow manure (39)
% of respondents compost and/or leave residues on soil	82	84	83	100

SI Table 2. Summary of growing surface and substrate type input use, waste management, and P balance, excluding the farm category. Weighted means are the total value of the management type where each survey response has been weighted by area cultivated. When not indicated as weighted, means are not weighted by area, thus each survey holds the same importance.

Management value	Soil	Mixed	Containers and roof-top farming
Weighted P balance (g of P/m^2)	35.7	14.2	33.5
Mean P balance (g of P/m^2)	26.71	50.19	60.75
Weighted % of P from on-island recycled sources	14	49	9
Mean % of P from on-island recycled sources	24	36	24
Mean number of inputs used	2.4	5.6	3.4
Input type most used (% of respondents)	Plant-based compost (31)	Plant-based compost (70)	Marine-based compost (48)
Weighted input contributing to P input most (% of total inputs)	Plant-based compost (32)	Plant-based compost (42)	Marine-based compost (41)
% of respondents compost and/or leave residues on soil	57	96	72

3.9.3 References

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CONNECTING STATEMENT

In Chapter 3, I quantified P flows in the food and UA systems of Montreal. I found that P recycling is currently very low in the city's food system, and that UA plays a quantitatively small role in the whole island's P cycle. Within the UA system however, I found that the majority of P applied to crops came from recycled sources. Although UA cannot recycle all the P contained in food and yard waste currently produced on the island of Montreal without overfertilizing, it seems that UA may be poised to act as a catalyst to increase P recycling on- and off-island. To more fully understand this potential, we must first understand the social, ecological, and technological drivers of P cycling and recycling in Montreal and other cities. In Chapter 4, I look to the literature to determine what types of driving factors one should consider to move from a simple quantitative understanding of urban P cycling to a more nuanced understanding of the context that surrounds, and often drives, these flows. Examining 18 published studies about cities from around the world using substance flow analyses methods, I categorize key higher-level drivers of P flows. Understanding these drivers of urban P flows will help determine how P cycling can be linked to other urban priorities and plans, as well as help select P management solutions that are adapted to a particular city and that maximize synergies and minimize negative tradeoffs between P flows and other resources.

4 URBAN PHOSPHORUS SUSTAINABILITY: SYSTEMICALLY INCORPORATING SOCIAL, ECOLOGICAL, AND TECHNOLOGICAL FACTORS INTO PHOSPHORUS FLOW ANALYSIS

This chapter is under consideration for publication: Geneviève S. Metson, David M. Iwaniec, Lawrence Baker, Elena M. Bennett, Daniel L. Childers, Dana Cordell, Nancy B. Grimm, J. Morgan Grove, Daniel Nidzgorski, Stuart White. Urban phosphorus sustainability: Systemically incorporating social, ecological, and technological factors into phosphorus flow analysis. Environmental Science and Policy.

4.1 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 are important in P movement and storage 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.

4.2 Introduction

4.2.1 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, Cordell and White 2013)). 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); however, this information alone may not be enough to instigate change in P management. Substance flow analysis (SFA, Baccini and Brunner 1991, Brunner and Ma 2009), which quantifies inputs, outputs, internal cycling, and storage, can be applied to any system in which P moves, such as a watershed (Likens 2013) or a city (Kennedy et al. 2010). Completing an SFA can help researchers and managers identify inefficiencies that might be problematic from a resource management standpoint. 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.

4.2.2 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 (Sterman 2006, Luke and Stamatakis 2012). 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 and municipal priorities (Talwar et al. 2011, Lang et al. 2012).

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 are 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.

4.2.3 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 what has been done has mostly focused on quantifying 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, the factors that Meadows and Wright (2008) and Childers (2014) tell us 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. Because each city is characterized by a unique context (Grimm et al. 2008), the specific P dynamics of a city varies, as well as the factors (and potential interventions) that drive these P dynamics.

4.3 Framework development

As a first step towards making urban P SFAs more relevant to urban decision-making and implementing 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 (P SFA publications from 18 international cities), combining the information gaps identified by P SFA authors (section 4.3.1) and the implicit driving factors used to calculate P SFAs (section 4.3.2).

4.3.1 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 4.1). 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 4.1 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 driving factors to 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.

4.3.2 Implicit factors

In calculating P SFAs, some important 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, 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.

4.4 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 important 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.

4.4.1 Categories of driving factors

For each category (Figure 4.1) 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 biophysical 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 affects 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 strongly affects the flows of P because different activities are characterized by different types of P flows (e.g., fertilizer application for agriculture or sewage exports from residential areas). 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 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 problematic inputs and pollution downstream 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 who are making decisions that affect P cycling, and 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 and it is important to identify "informal" actors or network of actors to understand those who are most important. 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 there are regulations banning P fertilizer on lawns in the city and landfilling organic waste, some households still used fertilizer and disposed of yard waste through municipal trash collection; it is thus important to consider more than regulations (Baker 2011).

Government and Regulation are the rules, regulations, and mechanisms of enforcement about how we manage land, resources, and waste. For example, in the Minneapolis/Saint-Paul, USA area, 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 in part be attributed 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. 2012a). The absence of a rule of 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 (Drangert 1998, Childers et al. 2011). Cultural values and perceptions are important to consider 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.

4.4.2 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 (Luke and Stamatakis 2012, Iwaniec et al. 2014).

4.5 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 4.1 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 casual 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.

4.6 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.

4.7 Next steps

The framework developed here is a pragmatic step towards 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 options, 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 priorities, 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).

4.8 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.

4.9 Acknowledgements

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4.11 Figures and Tables

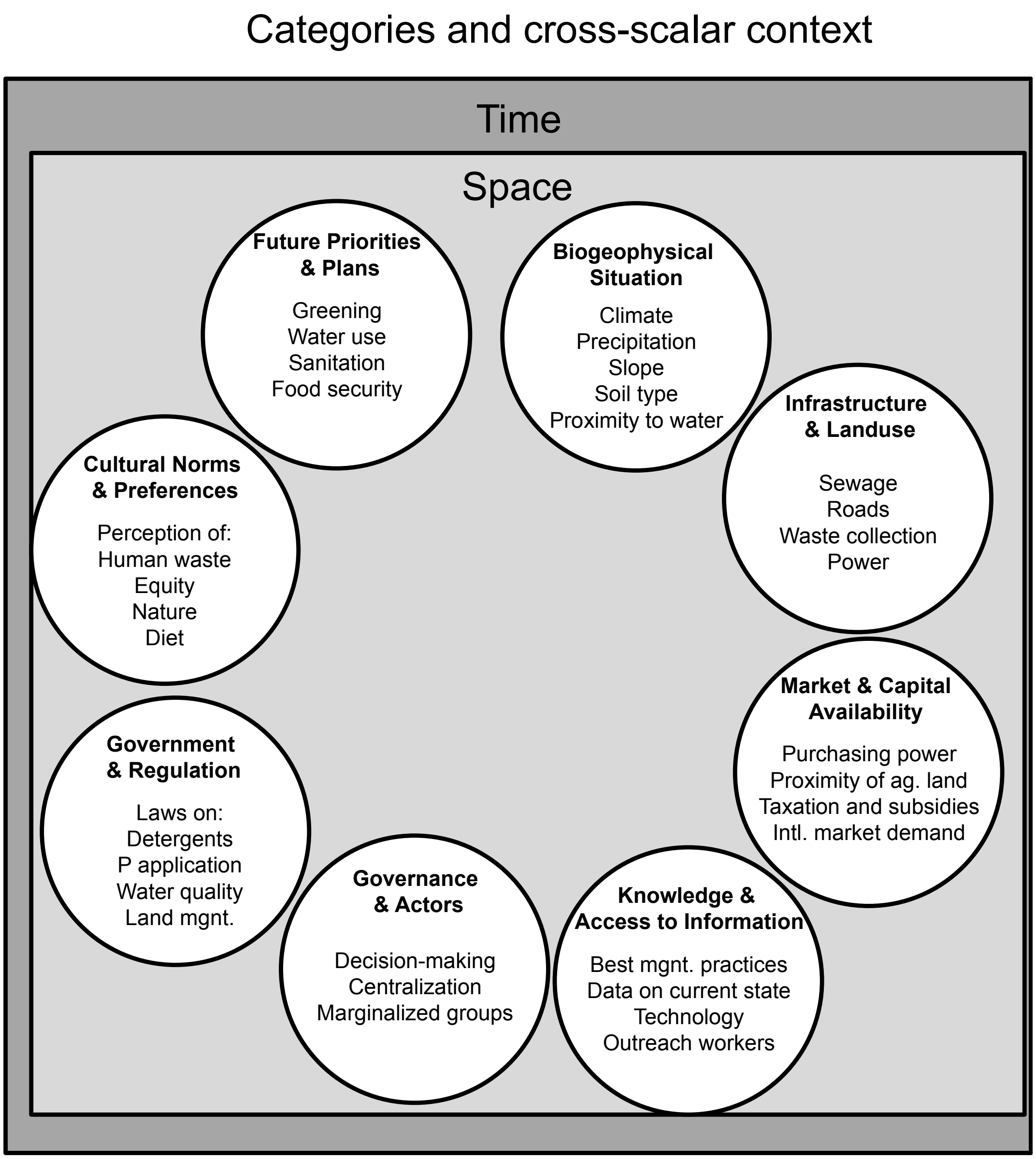

Figure 4.1 Framework. Categories of social, ecological, and technological factors that affect urban P stocks and flows and examples of specific driving factors to consider for each category. The Time and Space boxes in the figure represent the importance of cross-scalar context that can be relevant to 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 in some cases a factor may map to more than one category.

Table 4.1 Additional knowledge needs identified by existing 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

City	Authors	P flows considered	Author(s) identified what other considerations need to be included to implement solutions and for decision-making
			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

City	Authors	P flows considered	Author(s) identified what other considerations need to be included to implement solutions and for decision-making
			-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)
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	-Cost assessment (among waste recycling solutions)

City	Authors	P flows considered	Author(s) identified what other considerations need to be included to implement solutions and for decision-making
		agriculture)	-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 (in review)	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 broader 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

City	Authors	P flows considered	Author(s) identified what other considerations need to be included to implement solutions and for decision-making
			(elements, water, and energy) -Synergies and tradeoffs with other urban goals
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 broader 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 -Future urbanization (including demographics and land use)
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)

City	Authors	P flows considered	Author(s) identified what other considerations need to be included to implement solutions and for decision-making
			-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 broader 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)

CONNECTING STATEMENT

In Chapter 4, I examined existing literature and proposed a framework to better integrate important social, ecological, and technological drivers of urban P cycling into quantitative studies of urban P. I now turn back to Montreal to focus on a particular city in which to apply the framework. Building on the quantitative results of Chapter 3, and the framework developed in Chapter 4, I revisit the Montreal case study to include the broader driving factors of P management and assess their relevance in improving P management in Montreal. I explore the barriers and facilitators to P recycling through composting from a qualitative perspective, examining the system of social, ecological, and technological factors that drive P flows in Montreal. I focus on how the Quebec provincial law on organic waste management and increased interest in urban agriculture, which were identified as potential facilitators or catalysts to P recycling in Chapter 3, fit within the broader context of waste management and agriculture on the island to determine if and how they may facilitate increased P recycling in the future.

5 INCREASING PHOSPHORUS RECYCLING IN MONTREAL: FACILITATORS AND BARRIERS

This chapter is under consideration for publication: Geneviève S Metson, Elena M Bennett (in review). Increasing phosphorus recycling in Montreal: facilitators and barriers. Ecology and Society.

5.1 Abstract

Cities have the capacity to play a key role in increasing efficiency of phosphorus (P) resource use and recycling because they are consumers of large amounts of P-dense food and producers of vast amounts of P-rich waste. However, most cities do not take advantage of this potential. For example, in Montreal, Canada, only 6 % of P in waste is currently recycled. In this article, we identify key barriers and facilitators for Montreal to achieve a high level of P recycling through composting. We determine the potential for urban agriculture to help increase P recycling. We used semi-structured interviews with key stakeholders (19), participant observation (over 1.5 years), and document review to identify the key facilitating and impeding factors. We found that a provincial law mandating 100% recycling of organic matter from cities has the potential to facilitate increased P recycling. However, lack of a shared vision about the role of government, private sector, and citizens in producing high quality compost is a barrier that inhibits recycling. Cultural inertia, and lack of knowledge and infrastructure also act has barriers to increasing composting. Urban agriculture, which benefits from strong citizen support, is both a consumer and producer of compost, could be a means to overcome some of these barriers. However some P sources, including recycled ones, may be less desirable for some urban agriculture projects, reducing the potency of this potential facilitator. In addition, limited access to potential garden space and training also reduce the ability of urban agriculture to help cities recycle more P. Investing in increasing social capital, specifically connecting urban agriculture and waste management objectives, and linking key stakeholders to co-create shared visions about how to produce high quality compost may act as a stepping stone towards increasing Montreal citizens' knowledge about, and support for, increasing P recycling.

5.2 Introduction

5.2.1 The importance of phosphorus, cities, and local context

Phosphorus (P) is an essential nutrient for agriculture, but can also be a major pollutant if not properly managed. Most fertilizer is produced using mined P, which is both limited in overall quantity and found primarily in just a few countries, leading to concern about P scarcity and the geopolitics of access (Cooper et al. 2011). Despite its global scarcity, situations of local overabundance occur when P runoff from agricultural fields or lawns reaches sensitive waterways or there is insufficient treatment of animal and human waste streams, where it causes eutrophication (Elser and Bennett 2011). Sustainable P management is a pressing problem; populations around the world are increasingly vulnerable to spikes in food prices that are partially driven by increasing fertilizer (P) prices (Cordell and Neset 2014), as well as to spreading eutrophication in water bodies around the world (Diaz 2001).

Cities, home to over 50% of the global population (United Nations 2011), have the capacity to play a key role in increasing sustainable P management through the food system because they are consumers of large amounts of P-dense food and producers of large quantities of high-P organic waste. Within cities, multiple factors can influence P flows. For example, dietary choices in cities have a large impact on the amount of mineral P required for agriculture (Metson et al. 2012). Similarly, the level of and technology use for sewage treatment in a city will affect P losses and water quality downstream of the city (Mihelcic et al. 2011).

Sustainable P management will require increasing P use efficiency and recycling throughout the food system, including P recycling from urban waste to agricultural land, though details of specific solutions will vary from location to location (Cordell et al. 2011, Cordell et al. 2012), as solutions are not “one size fits all” (Smith et al. 2005, Tödtling and Trippl 2005l). In the urban context, increasing efficiency will include decreasing food waste, eating less meat, and ensuring correct fertilizer applications to landscaping and urban agriculture. Increasing recycling will include composting green waste and food waste for re-use as fertilizer, as well as using properly treated sewage waste to produce fertilizer for agricultural production. The relevance of solutions will vary based on the dynamic interplay of the social and biophysical factors that drive P cycling in that city (Folke et al. 2002, Alberti 2008). Previous research has identified eight key factors that drive and regulate urban P cycling: 1) biogeophysical situation, 2) infrastructure and land use, 3) market and capital availability, 4) knowledge and access to information, 5) governance and actors, 6) government and Regulations, 7) cultural norms and priorities, and 8) future priorities and plans (Metson et al. in reivew). Incorporating city-specific factors in these categories to a quantitative understanding of P could increase out understanding of urban P cycling, and help suggest P management strategies that take into consideration local context.

The social components that drive urban P cycling are particularly important but have been understudied in past urban P studies (Kennedy et al. 2010, Baker 2011, Chowdhury et al. 2014). Because change, adaptation, and innovation are dependent on multiple actors and their relationships, social capital (i.e., the social networks, bonds, and norms a community shares (Pretty 2003)) can be considered a key part of our capacity as humans to alter how we manage resources through collective action in the face of change (e.g., climate change (Adger 2010) and agriculture (Heemskerk and Wennink 2004)). High social capital is characterized by high trust, reciprocity and exchanges within the group, a shared understanding of rules and norms, and connectedness, and thus viewed as an important part of sustainable resource management (Putnam 1993, Pretty 2003). Increasing social capital can help create a shared understanding of a problem, or vision towards the future, allowing different actors in the system to collaborate on and integrate innovative solutions in the context of sustainability (Smith et al. 2010). Understanding which city-specific factors drive or regulate P cycling, as presented in Metson et al. (in reivew), can help us see how social capital is contributing to current P management as well as social capitals' capacity to help implement solutions in the future.

In this article we use Montreal, Quebec, Canada as a case study to explore locally relevant driving factors, and their relationships to one another, in order to identify barriers and facilitators to increasing P recycling through composting. We build upon a quantitative analysis of P flows in the food and urban agricultural systems of the island of Montreal (Metson and Bennett in reivew), and explicitly look at the factors driving the current low levels of P recycling in the system and how these factors may affect future P recycling.

5.2.2 Montreal case study

The island of Montreal, Quebec, Canada (which includes the city of Montreal and 17 smaller municipalities, which we refer to as Montreal in the rest of the article) is located on the Saint-Lawrence River. Once a mostly agricultural settlement, it is now the most densely populated area of the province of Quebec, home to 24 % of the provincial population (Canada Economic Development for Quebec Regions 2010). Montreal is a major port city that historically supported a much larger industrial sector (Lewis 2001), even including a cement quarry on its territory. Because of this history of industrial production and land use, some neighborhoods now have high levels of heavy metal and hydrocarbon contamination, affecting modern land use decisions (Ville de Montréal 2014b).

Montreal employs a similar waste management approach as other modern cities in North America, treating a high proportion of its waste to minimize certain environmental externalities, but continuing to apply an "out of sight, out of mind" management philosophy that externalizes problems by putting them elsewhere. Until 1984, the city disposed of all its untreated sewage waste directly into the Saint-Lawrence River. While the city began treating sewage in 1984, it wasn't until 1996 that the whole island was connected to the sewage treatment plant (Ville de Montréal 2014c). Solid waste (including food and green waste that are high in P) was landfilled on the island until space limitations began to move landfilling progressively off-island. The last on-island landfill was closed in 2009 (Front commun québécois pour une gestion écologique des déchets 2002, Ville de Montréal 2014a). Montreal now pays high landfilling costs for its solid waste to be trucked off the island (Ville de Montréal 2009). Currently, 89% of organic waste produced on the island is landfilled, but a Provincial government mandate (MDDEP 2009), which was formally adopted in Montreal's waste management plan (CMM 2008), requires municipalities to divert 60% of their organic waste from landfills by 2015, and 100% of their organic waste must be diverted by 2020.

The physical setting of Montreal, its history, and its current land use, consumption, and waste management practices all shape the P cycle on the island. Phosphorus entering the island of Montreal as food mostly accumulates in landfills (approximately 2.63 Gg P yr^{-1} which includes P from biosolid incineration at the wastewater treatment plant and municipal solid waste collection, Metson and Bennett (in reivew)). Just 6% of P in food and green waste is composted. The food produced by the urban agriculture (UA) system and consumed on-island only represent about 0.44% of all P consumed by island residents. Overall, 73% of P applied to UA was from on-island recycled sources in 2012. UA plays a small quantitative role in the Montreal P system as a whole, but practitioners of UA seem to favor recycled P sources as fertilizer. Although UA could not recycle a large proportion of P in food and green waste (in large part because of space limitations on the island), composting through UA could possibly act as a catalyst for broader scale change, by changing people's relationship to the food system, translating in to more sustainable P management at the regional scale (Metson and Bennett in reivew). This quantitative analysis of P flows is a key component towards understanding how we can manage P more sustainably, but does not fully explore the factors that drive and regulate these flows and thus how we can change them.

In summary, Montreal is an example of a city where P recycling is currently low, where waste management practices do not yet encourage high waste reuse, but where increasing concerns about sustainability, and specifically increasing UA and changing organic waste management practices, may be creating a situation to bring about change. However, more information is needed to understand if and how the city will accomplish their sustainability goals. A better understanding of what facilitates and restricts current composting practices, as well as identifying the factors that act as facilitators and barrier to future composting could help us understand the potential of interventions to increase P recycling. The goal of this article is thus to address the following question:
What are the key barriers and facilitators for Montreal to achieve high P recycling through composting, and what role could UA practices play in increasing P recycling?

5.3 Methods

We used a case study framework (Yin 2003) and grounded theory (Glaser and Strauss 1967), combining three data collection methods in order to iteratively build a list of facilitators and barriers to sustainable P management in Montreal (using qualitative methodologies described in Creswell (2013)). We used grounded theory to ensure that we remained open to emergent themes (i.e., inductive process of building an understanding of the system of interest based on collected data) because we were interested in identifying factors specific to Montreal, which could then be linked to more general and theoretical concepts of barriers and facilitators to social change in the literature (Glaser and Strauss 1967). Our research design maximized content validity by ensuring we considered the full scope of facilitators and barriers that may occur within the boundaries of our system. We tackled the complexity of the system and potential biases in reporting with triangulation among our three data collection methods (Thurmond 2001, Creswell 2013), increasing validity. Multiple measures can be used throughout the research process to ensure the validity of a qualitative study (Whittemore et al. 2001), and here we focused especially on a prolonged engagement in the field and the use of multiple lines of inquiry in our research process. As we were particularly concerned with gaining a detailed understanding of the unique Montreal system, our findings may however not be highly generalizable (i.e., limited external validity).

In May 2014 we conducted semi-structured interviews with 19 key stakeholders in the system. Key stakeholders were identified through snowball sampling throughout the participant observation process, and were selected for their access to multiple types of knowledge about composting, waste management, and UA, which we expected would lead to a broader view of the system (Marshall 1996). These key stakeholders were based in city and municipal departments (n=4), universities (where the stakeholders involved in pertinent research topics and were also involved in community outreach or journalism (n=6)), environmental education groups (n=6), and private companies in UA and composting (n=3). We asked these key stakeholders two open-ended questions: 1) What do you view as facilitators and motivators to composting in Montreal, and 2) What do you view as barriers to composting in Montreal. Follow-up prompts to questions were informed by participant observation and document analysis to help focus interviewees (see SI Material for full interview scripts and REB approval). Interviews lasted between 8 and 19 minutes, were recorded and transcribed, and analyzed using *Dedoose* software.

Participant observation took place over a year and a half (August 2012 thru May 2014), through visits to gardens and farms to conduct quantitative surveys of P management (see Metson and Bennett (in reivew) for survey design and questions), and through public events (including municipal sponsored events, and community and NGO meetings and events). Through discussion with practitioners individually, and through group presentations and discussions, it was possible to iteratively narrow the list of initial factors that may be important to the Montreal context to those that were indeed important, and expand research into those locally relevant themes or factors. Information was recorded in field notes, meeting minutes, and in the "additional information" section of the survey forms on P management administered in gardens and on farms. Participant observation allowed the research team to gain a much fuller picture of the Montreal system and provided a way to better analyze interview data.

As participant observation and interviews focused on UA and waste managers, document review was an essential step towards understanding the issues of food and waste management that pertain to the broader Montreal community. We reviewed key government policy documents and reports, including public consultation reports that included hundreds of citizen and group reports filed with the City's public consultation commission. We also reviewed media coverage of events related to organic waste management and UA in both French and English, focusing on the implementation of the Montreal waste management plan (thus reviewing documents and media coverage from 2008 when the policy was announced through July 2014). In addition to locally-specific document review, we considered a broader list driving and regulating factors that may be relevant to the amount of UA, and fertilization and waste management practices, based on the American Planning Association's list of important characteristics to consider for UA (Hodgson et al. 2011).

We used coding and content analysis (conventional coding as defined by Hsieh and Shannon (2005)), as well as constant comparison methods (Glaser and Strauss 1967) to analyze interviews, and to complement data from interviews with information from participant observations and document review. Coding involved assigning categories to interview passages, first allowing the categories to emerge from the interview material, and then recoding to include theories emerging from the review of other data sources and the peer-reviewed literature, until clear themes could be identified. We use direct quotes in the results and discussion section of this article to represent the themes that emerged from the analysis. The process of data analysis was highly iterative; we constantly reevaluated the evidence presented in all data sources to identify both reoccurring themes and divergent perspectives about themes. Through this reflexive process, allowing emergent themes to reveal themselves, we focused on key driving factors that created barriers and facilitators towards increased P recycling, keeping Metson et al. (in reivew) driving factor categories in mind.

5.4 Results and Discussion

We identified a large set of factors that influence P cycling and recycling on the island, focusing on key facilitators and barriers to increasing P recycling in Montreal (see Tables 5.1 and 5.2 for a full list of factors, data sources, and their importance to P recycling in Montreal, and SI Table 1 and SI Table 2 for the occurrence of themes in interviews). In the following sections we expand on 1) the facilitators and barriers that affect P recycling at the whole-island level, 2) the facilitators and barriers to P recycling within the UA system, and 3) a path that takes advantage of existing facilitators to overcome barriers.

5.4.1 City-wide waste management facilitators and barriers to P recycling

5.4.1.1 Facilitators

The key facilitators that could increase P recycling at the whole island scale are a law on organic waste management and the existence of many small scale composting projects. Citizens compost at home, through Éco-quartier projects (borough level environmental awareness organizations), through private companies (e.g., Compost Montreal), and through select borough pilot projects (e.g., Rosemont borough), or smaller municipality organic waste collection programs (e.g., Cote-Saint-Luc). Environmental organizations see an increasing citizen interest in composting. As one stakeholder puts it:

“People are more and more concerned [about doing something with biodegradable waste]. Their number one concern seems to be the environment. People who come to see us really come because they know the effects landfills have.”

Motivators to participate in separate organic waste collection and composting include individual environmental consciousness, and a need for fertilizer for gardening. Borough and municipality desires to comply with the Quebec waste management law also motivate some projects across the island. Successful participation in composting seems to happen when citizens are knowledgeable about proper composting techniques, and the process of waste separation and/or composting is made easy and accessible. The qualities of "easy and accessible" vary by scale of project and by type of people involved. Examples of "accessible" infrastructure characteristics include having enough space for home composting, being in walking distance of community compost, and having access to free organic waste collection bins and bags that are adapted to family size.

The Quebec provincial government enacted a law mandating that cities divert 100% of their organic waste (food waste, green waste, and biosolids) away from landfilling by 2020 (CMM 2008, MDDEP 2009). This law should, in theory, increase P recycling on the island of Montreal because it requires the city to divert high P waste from landfills and produce a reusable compost product (Figure 5.1). Governments (provincial and municipal) were motivated to put such a law into place because they were concerned with the space landfills take away from other land uses, their contribution to climate change, and the possibility of long-term environmental pollution to soils and water (MDDEP 2009). Montreal plans to comply with this law by producing compost that can be reused, even if that was not the primary motivation. A key stakeholder says:

"In the municipal waste plan, our objective was really to produce a very good quality compost. Our treatment technology choices were made to do so. We will make sure it's safe and make a high quality compost."

Despite these important facilitators, and even though the Montreal waste management plan was adopted unanimously by council members after public consultation showed general support for the project, the City is not on track to meet these goals (Robillard 2013, Beaudin 2014). Key barriers stand in the way.

5.4.1.2 Barriers

Although easy access to infrastructure and sufficient knowledge of composting has allowed some composting to flourish at smaller scales in the city, existing habits, conception of waste as "dirty", and a lack of ease and knowledge is hindering broader scale adoption of composting

(Figure 5.1). To divert food and yard waste from landfills, the City must collect organic matter separately from other solid waste and recyclables, and treat the organic matter so that it can be reused. Citizens have yet to fully embrace the idea of separate organic waste collection and composting. Concerns over organic waste bins being smelly and attracting flies, maggots, and rodents are widespread (58% of key stakeholders discussed it in interviews), increasing the challenge of changing existing habits of not separating organic from non-organic waste. A lack of information and knowledge, and existing misinformation, about waste separation and composting also remains a barrier to the adoption of the waste management plan. Even in boroughs that have piloted organic waste collection, thus providing infrastructure to citizens, have not all been successful because of a lack of initial information dissemination about the project, and follow-up with citizens about problems after implementation of the pilot programs. As one key stakeholder puts it:

"…people were not necessarily well informed on how to compost. I am talking about the little brown bins that are collected each week in boroughs that are composting. For example, in the summer people often skip a week [of putting the compost bin to the curb] and then, in no time, there are maggots and worms in the bin. People will often be disgusted, they won't want to clean, and then it's over. We will have lost those people, they will no longer be interested in composting after that."

In the past, Montreal put in place infrastructure to separate urban populations from their waste to reduce disease and increase general cleanliness (Melosi 2005). However, this practice has created cultural and knowledge barriers to viewing organic matter as a "clean" resource when properly treated.

As a large and dense city, producing much more organic waste than could be managed and reused by individual citizens (Metson and Bennett in reivew), Montreal is building five large organic waste processing plants (two which will do biomethanation to produce energy from the organic waste decomposition process) to fulfill the City's waste management plan objectives. However, the City has had difficulty finding sites to build the processing plants they need. One key stakeholder says: "Where are we going to compost? We know this is the big fight: not here, not where I live, not where he lives…, finding a site for compost processing is an issue." This difficulty in site identification was also clear throughout Montreal's public consultation procedures and media coverage (see Table 5.1 for sources).

One of the sites proposed by the City initially, the Saint-Michel Environmental Complex, is a particularly poignant example of the political, social, and economic history and context surrounding some of the "Not in My Backyard" attitudes (NIMBYism) that exist in Montreal about composting. The Saint-Michel site was initially a cement quarry, then transformed into a landfill. The site was one of the last landfill sites to be decommissioned on the island (stopped receiving putrescible waste in 2000, and dry construction waste in 2009) and is located in the densely populated borough of Villeray – Saint-Michel – Parc Extention. Currently, the site houses a small municipal open-air composting operation, but there has been strong citizen and political opposition to building a larger indoor composting facility (including petitions, and municipal election platforms see Table 5.1). Residents were concerned about noise and smells associated with having an organic waste processing plant near their homes. One key stakeholder said:

"I think [the political opposition to the Saint-Michel site] is merited, because [the City] has violated the rules laid-out by the Ministry to protect peoples well-being in siting those locations [being more than 150m from residences]."

Ultimately, the Quebec Minister of the Environment did not approve Saint-Michel as a location for the composting plant (see Table 5.1), and the City has now proposed the purchase of private land in the Rivière-des-Prairies-Pointe-aux-Trembles borough as an alternative site (Chapdelaine 2014). The City has faced similar lack of local "buy-in" at other proposed sites (Marchal 2012, OCPM 2012b), making it difficult to move forward with the implementation of the City waste management plan.

In addition to barriers associated with organic waste collection and processing, there exist barriers associated with different stakeholder views about the appropriate scale of composting and compost quality, and thus act as barriers to compost use in and around the city (15 out of 19 interviews discussed the importance of compost quality at many scales). Many stakeholders believe that large-scale composting projects do not produce high quality compost because the waste used to produce it could be contaminated (non-organic waste can be mixed in the organic waste including plastics and metal) and/or because highly processed foods do not produce high quality compost. An underlying assumption is that smaller scale composting can ensure more traceability of materials, and thus higher quality compost. As such, some believe that large-scale compost production is a waste management strategy, and not an option for reuse in agriculture (only in horticulture). One stakeholder sums up this view by saying:

“Waste management and the producing a good end-product for gardening are two separate worlds. It’s a real mistake to try to glob those two things together.”

A lack of “buy-in” by one important stakeholder may impede the whole system from working. One stakeholder says:

“I think that from the moment where one actor, one borough, isn't on-board, it slows down the whole process. […]if one actor doesn’t participate, there is a lack of awareness, then there is a risk that costs will go up for all the other actors.”

Overall, the provincial law on the recycling of organic waste should facilitate the reuse of P in Montreal, but current infrastructure for collection and processing, as well as a lack of political and cultural support for the collection, processing, and reuse of organic waste, translate into currently low recycling of P in the system (although smaller subsets of the population to successfully recycle P though composting). As such there seems to be an uncertain future for increasing P recycling through composting (as noted by the question marks in Figure 5.1). There exists a lack of trust and knowledge among different actors in the system, in addition to different norms about what can and should be reused. These lacking elements point to low social capital hindering Montreal’s ability to successfully implement a law that could increase P recycling.

5.4.2 Facilitators and barriers to P recycling in urban agriculture specifically

Urban agriculture (UA) requires P inputs to produce food, making it an integral, although small, part of Montreal P cycling (Metson and Bennett in reivew). Increasing the area dedicated to UA and the amount of locally-recycled P applied to this area are two ways UA can contribute to increasing urban P recycling. Understanding the factors that facilitate and constrain the urban area under cultivation, the type and amount of P fertilizer application, stakeholder's feelings about changes to the type and amount of fertilizer applied to plots, and waste management practices is key to determining the role UA can play in P cycling.

5.4.2.1 Facilitators

Practitioners of UA are more inclined to participate in composting than average Montreal residents because they have more knowledge of composting, access to composting sites, and have a use for compost; these factors act as facilitators. Many, if not most, current UA practitioners share a desire to move towards alternatives to conventional, high-input and high-waste, systems. Compost production can be one way to achieve such a goal. Metson and Bennett (in reivew) surveys with local UA practitioners revealed that the majority of them practiced some type of green waste or food waste recycling strategy. "Generally, [urban agricultural practitioners] need compost to ensure their plants are productive and to fertilize their soil. Needing compost is a motivating factor" (key stakeholder). UA is thus both a compost producer and a compost user, creating an incentive to seek-out tools (e.g., composting bins), space, and knowledge to do it properly. As such UA can support increased P recycling on the island.

The island of Montreal has seen a sharp increase in interest in UA in recent years, which should lead to increased P recycling (Table 5.2). More than 29 000 residents signed a petition in 2011 to initiate a public consultation process about UA (in support of increasing UA) with the City through the Office of Public Consultation of Montreal (OCPM). In October 2012, the OCPM produced a recommendation report for the City, where it summarized the thoughts of 15 000 participants and 103 written statements submitted during the consultation process. The report specifically mentions the importance of compost in UA, and suggested that the City of Montreal should create of a permanent committee to support and coordinate UA efforts, which was done in 2013 (OCPM 2012a). In addition, the Conférence régionale des élus de Montréal (CRÉ) has created a Montreal food-system plan. The plan is a guide for Montreal to develop a sustainable and equitable food system. One of the plan's core themes is to reduce the ecological footprint of the city's food system, through measures such as reducing food waste, increasing food waste recycling, and increasing local production in UA (CRÉ 2014). Together the OCPM recommendations and the CRÉ plan support more efficient use of P (decreased food waste), more local compost production (and thus recycled P), and a market for compost (through increased area of UA).

5.4.2.2 Barriers

Some types of UA might discourage the use of certain P fertilizers (including compost), and as such this can act as a barrier for UA to increase P recycling on the island. Individuals and groups have different motivations for participating in UA (Duchemin 2013), and as such use different nutrient management practices, all of which do not favor P recycling equally. For example, educational UA projects often have rules to ensure that participants, including children, are not in contact with any type of heavy metal, organic, or pathogen contamination. As such, non-certified inputs, and composting on-site may be discouraged. One key stakeholder says, "schools also have public health guidelines, and if they want to compost at school, I know with the School Board, there are guidelines for on-site home composting." Because city compost comes from large scale collection, there is a potential of contamination; thus, most educational projects prefer not to use City compost. Concerns about city soil contamination also means that education-oriented UA is often done in containers, and practitioners cultivating in containers tend to use less recycled sources of P as fertilizer (Metson and Bennett in reivew).

In addition to barriers to using compost in UA, there are also factors that limit the presence and expansion of UA overall. Many current UA practitioners feel that a lack of physical and monetary capital is hindering local UA endeavors and future expansion (OCPM 2012a). Limited financial resources allocated to UA by the municipality (and other government levels), as perceived by stakeholders in the system, may be creating situations where there is a lack of knowledge about proper P application and proper composting. Specifically, cuts in financial resources has resulted into less horticultural councilors in community and collective gardens, and access to such specialists for private gardeners as well. Although spatially variable, there is a lack of space to practice UA (e.g., waiting lists in community gardeners), and lack of financial resources to transform spaces that could be used for UA.

5.4.3 Opportunities to overcome barriers by using UA as a catalyst

UA production may not be a large quantitative P recycler (Metson and Bennett in reivew), but it may indeed act as a catalyst for larger scale compost production and reuse. A focus on UA could be a way to fully realize and synergize the benefits of two key facilitators toward P recycling: 1) the law on organic waste diversion and, 2) the large public support for increase UA (Figure 5.2). When speaking about the role of UA in Montreal's compost production, one stakeholder said:

"… I focused on urban agriculture in my neighborhood since I arrived at the organization 4 years ago. I feel like it is the window, or the door, that allows you to engage on the whole landscape of environmental themes".

Montreal residents want more UA (as seen through the public consultation process) and this can align with P recycling and composting goals if stakeholders can create a shared definition of "high quality" compost such that UA becomes a bigger user of larger-scale composted P, and there is trust between stakeholders in the system.

Based on interviews and participant observation, there are four key elements that must be present in Montreal for P recycling through composting to be successful: 1) Knowledgeable citizens, 2) Ease of practice through infrastructure, 3) Compost as a valued product (thus high quality), and 4) Monitoring to ensure adherence to a composting program and continued high quality compost product. Based on our understanding of the Montreal system, we believe support for UA may in fact support larger-scale P recycling by engaging elements 1, 3, and 4. The permanent committee on UA (based on the OCPM recommendation) and the Sustainable Montreal Food System plan (CRÉ 2014) may present two opportunities to educate about, support, and monitor composting. They could serve as starting points for "innovation platforms", an infrastructure for actors with diverse types of knowledge and resources to come together to find innovative solutions to a problem, while meeting multiple goals at once in a complex system (as shown in Consoli and Patrucco (2008)). Both of these initiatives act as shared spaces between the City, and citizens and organizations (and could include universities). As such, these initiatives can act as facilitators for the co-creation of a high quality compost definition by building social capital.

A shared, or coproduced, waste management plan, based on a common definition of " high quality" compost, could ensure that UA practitioners and local farms trust and use Montreal compost (i.e., a valued product they trust). In fact, the majority of the stakeholders we interviewed expressed that combining both small scale and large scale composting as a possible and desirable path to take, indicating that increasing composting through UA could indeed be complementary to larger scale processes. Sixteen out of 19 interviewed stakeholders discussed the roles and responsibilities of actors in the system in such a way that favored the involvement of individual citizens, all the way to municipal government in compost production. In addition, nine stakeholders explicitly mentioned UA as a catalyst to increasing composting, not only as a small-scale producer and user of compost. As described by one stakeholder, we must take a multi-pronged approach in order to achieve organic waste recycling, where people trust the end-product:

"Cities must take care of [composting] and the provincial government as well. The citizen is at the base of the whole concept, if he wasn't here there wouldn't be any organic waste. Yes, we need to centralize, but it should be a bottom-up process that takes into consideration citizen participation."

Increased funding for UA projects could further contribute to increasing knowledge of practitioners and the general public, thus directly increasing small scale composting, and indirectly decreasing negative perceptions or misconceptions about organic waste reuse at larger scales. In addition, it would be beneficial to implement monitoring programs on UA practices, citizen concerns, and on compost quality, so that the City may constantly reevaluate their outreach and compost production to ensure that they are meeting citizen expectations and environmental objectives. Using UA as a building block, or a catalyst, may actually decrease the need for large scale monitoring and enforcement around organic waste separation because building on existing desires (i.e., UA) in the city and increasing social capital can decrease transaction costs by creating a shared understanding of why compost is being produced (Isham 2002).

Our analysis of increasing P recycling in Montreal and the barriers we identified, are similar, in general terms, to literature about other complex environmental challenges and how a lack of social capital and trust can sometimes be a larger barrier to change than physical or economic capital. Although studies on urban P management have not often explicitly considered the role of social capital, studies on urban climate change adaptation and mitigation have. For example, Burch (2010) found that successful implementation of climate mitigation and adaptation plans, overcoming path dependency in municipal institutions, was more about building on existing capacity by fostering a culture of collaboration, leadership, and innovation, rather than investing in new policies or resources in the Vancouver metropolitan area. We can draw parallels between the situation described by Burch (2010) about Vancouver's climate change policies, and Montreal's organic waste management. In both cases there exists facilitators towards more sustainable resource management in law, and in general public desire, but inertia of current culture and organization can act as barriers to taking advantage of these facilitators. Investing in social capital to increase trust may be one way to overcome these barriers, where building on existing capacity within the cities is possible.

5.5 Conclusion

Cities are hotspots for P cycling because they concentrate both demand for P and the production of high-P waste. As such, developing locally adapted P management strategies for cities around the world is key to local and global P sustainability. In every city, there are facilitators – factors that encourage P recycling – and barriers – factors that discourage it. In Montreal, a law mandating 100% organic waste recycling by 2020, and recent support for UA, act as facilitators towards more P recycling. But in order for Montreal to take advantage of such synergies, it will be necessary to increase knowledge and trust among actors and build an infrastructure and culture that is conducive to compost collection, processing, and reuse. A lack of social capital, especially tensions between the role of large-scale centralized compost production and small-scale production, hinders the implementation of any P recycling plan. Closer collaboration between waste management and UA sectors may be one way to increase P recycling by 1) increasing citizen knowledge about composting, 2) creating shared definitions about compost quality, 3) increasing trust among actors, and 4) implementing continuous monitoring, in order to overcome barriers to P recycling. Although Montreal currently recycles only small amounts of P, more recycling seems possible by focusing on existing synergistic municipal priorities, and using them as a type of "innovation platform" to increase social capital in order to implement a composting plan that increases P recycling.

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5.7 Figures and Tables

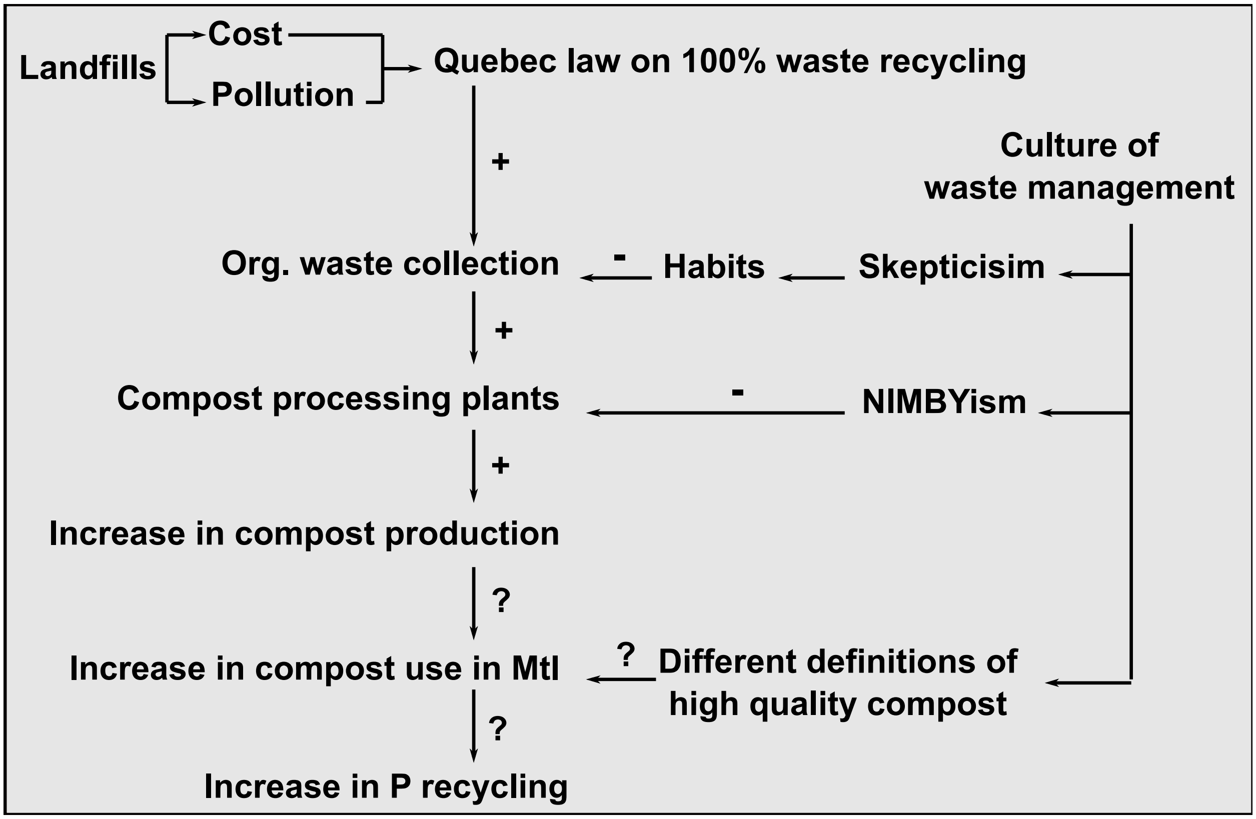

Figure 5.1 Factors influencing the level of P recycling on the island of Montreal. The Quebec law on organic waste recycling is a major facilitator to increasing P recycling, but barriers caused by the current culture of (and beliefs about) waste management acts as a barrier to the full implementation of the law. Arrows indicate influence or causal relations. Plus signs (+) indicate and increase or a positive effect towards P recycling, minus signs (-) indicate a decreasing or negative effect towards P recycling, and question marks (?) indicate that that the effect and outcome are uncertain with respect to P recycling.

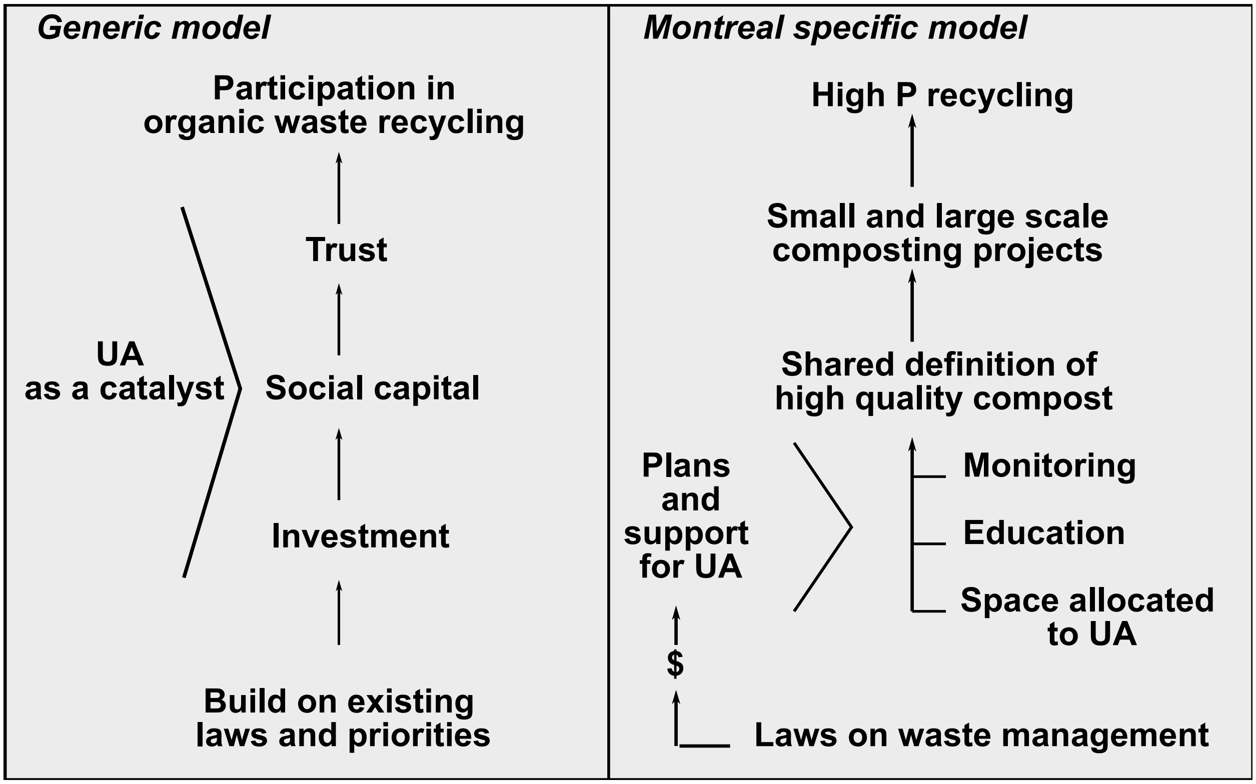

Figure 5.2 Model to overcome barriers to increasing P recycling, taking advantage of existing facilitators. The *Generic model* shows how increasing trust by investment in urban agriculture (UA, an existing priority in Montreal) could increase social capital and trust. The *Montreal specific model* shows which laws and priorities can be used, and what types of investment could lead to increase P recycling on the island based on our study.

Table 5.1 Lines of evidence used to select relevant factors acting as facilitators and barriers to P recycling through composting in Montreal. "✔" indicates that the line of evidence is used. Specific data sources for document review are provided in the last column, while specific interview themes we identified are listed in SI table 1. This represents the full list of factors identified, where normal font ones were used as key factors to develop the Results and Discussion section, while the *italic* factors were not deemed key.

Factors	**Semi-structured interviews**	**Participatory observation**	**Document review**	**Document sources**
City level				
Quebec law on organic waste management	✔	✔	✔	(CMM 2008, MDDEP 2009)
1st world view of waste management	✔	✔	✔	Not Montreal specific: (Drangert 1998)
Ageing infrastructure	*✔*	*✔*	*✔*	*(Vérificateur général de la Ville de Montréal 2013, Commission sur les finances et l'administration de la ville de Montréal 2013)*
Central, mixed, and no-recycle sewage system		*✔*	*✔*	*(Ville de Montréal 2014c, Godmaire and Demers 2009, Sierra Legal Defence Fund 2004)*
Landfilling of most organic waste (w/small composting projects)	✔	✔	✔	(Ville de Montréal 2013a)
"NIMBYism" about large scale composting	✔	✔	✔	News and public reports: (Beaudin 2014, CBC 2012, Chapsal 2013, Chapdelaine 2014, Community Economic Development Corporation Centre-Nord,2013, Corriveau 2013, Lacerte 2014, Marchal 2012, OCPM 2012b Panton, 2013 Radio-Canada 2013)
Waterway characteristics, no eutrophication around Mtl			*✔*	*(Environment Canada 2013b)*
Diet			*✔*	*(Metson and Bennett in reivew)* *Not Montreal specific: (Metson et al. 2012)*
Understanding of proper collection and composting	✔	✔		
Compost Market	✔	✔	✔	(Recyc-Quebéc 2012)
Density	✔	✔		Not Montreal specific: (Hodgson et al. 2011)
Perception of actors roles and responsibilities	✔	✔		
Urban agriculture level				
Amount of urban agricultural	✔	✔	✔	(Metson and Bennett in reivew, OCPM l 2012a, CRAPAUD

Factors	Semi-structured interviews	Participatory observation	Document review	Document sources
and urban food system initiatives				et al. 2013, Conférence régionale des élus de Montréal 2014) Not Montreal specific: (Hodgson et al. 2011)
Understanding of larger environmental and social problems in the food and/or waste system	✔	✔	✔	(Duchemin 2013)
Desire for education and outreach	✔	✔	✔	(Duchemin 2013)
Desire for "organic"	✔	✔	✔	(Duchemin 2013)
Access to capital for food	✔	✔	✔	(Ville de Montréal 2013b) (Duchemin,2013)
Concern about soil quality		✔	✔	*(Office de consultation publique de Montréal 2012a, Direction de la santé publique de Montréal 2008,Beausoleil and Price 2010) Not Montreal specific: (Hodgson et al. 2011)*
Substrate use	✔	✔	✔	*(Metson and Bennett in reivew)*
Quebec laws on Environmental quality and agriculture & Quebec law on water quality	✔	✔	✔	*(Ministère du Développement durable Environnement et Parcs 2013b, Ministère du Développement durable Environnement et Parcs 2013a)*
Choice of inputs and amounts (including fertilizer purchase, and availability of inputs)	✔	✔	✔	(Metson and Bennett, in reivew, Pfeifer and Bennett 2011)
Rules in community gardens and UA	✔	✔	✔	*(Office de consultation publique de Montréal 2012a)*
Knowledge of proper composting (often limited)	✔	✔		Not Montreal specific: (Hodgson et al. 2011)
Access to capital for UA projects (often limited)	✔	✔	✔	(Office de consultation publique de Montréal 2012a) Not Montreal specific: (Hodgson et al. 2011)
Impervious surface cover			✔	*(Pfeifer and Bennett 2011)*
Land ownership/tenure	✔	✔	✔	*Not Montreal specific: (Hodgson et al. 2011)*
Amount of different types of land use	✔	✔	✔	*(Metson and Bennett in reivew)*
Access to fresh water (unlimited)			✔	*Not Montreal specific: (Hodgson et al. 2011, Smit and Nasr 1992)*
Crop choice			✔	*Intermediate between other factors*
Sunlight hours			✔	*Not Montreal specific: (Hodgson et al. 2011)*
"Short" growing season			✔	*Not Montreal specific: (Hodgson et al, 2011)*

Factors	Semi-structured interviews	Participatory observation	Document review	Document sources
High temperature and precipitation variability and average low temperature			✔	*Not Montreal specific: (Hodgson et al. 2011)*
Needs to overcome barriers towards more P recycling in City and UA				
Knowledgeable citizens	✔	✔		
Valued compost product	✔	✔		
Ease of practice through infrastructure	✔	✔		
Monitoring	✔	✔		
High compost quality (shared definition)	✔	✔		

Table 5.2 Justification of factors that act as facilitators and/or barriers to recycling of P through composting of food and green waste in Montreal and within the urban agriculture (UA) systems. For each factor (column 1), we explain its general importance to urban P cycling (column 2), as well as the situation in Montreal (column 3). Factors in normal font are key factors used in the Results and Discussion section of the article while the factors in *italic* were deemed to be secondary.

Factors	**Importance of factor to urban P recycling**	**Specific Montreal situation**
City level		
Quebec law on organic waste management	Motivation for local compost production and thus increases availability of recycled P fertilizer	60% of organic material recycled by 2015 and zero organic waste (food, green, and sewage) sent to landfills by 2020 (thus 100% recycling and/or reduction in waste)
1st world view of waste management	Do not view waste as a resource (rather something we must get rid of because it is dangerous) thus limits P recycling.	Currently some reticence to reuse compost made by the city, and concerns over odor, and pests associated with compost collection and processing
Ageing infrastructure	*Can mean leaky sewage system thus loss of P, but also that there are other pressing priorities for money in the city and not necessarily P, although there are opportunities if we are rebuilding to change infrastructure. In addition, built infrastructure creates a legacy for current P cycling.*	*Most major built infrastructure projects date from the 60's and 70's and need considerable repair (e.g., Champlain Bridge, Turcot Interchange, Olympic stadium). Currently Montreal has underspent in updating sewage and water infrastructure (and subject to overspending through corruption), and a large part of the budget is now dedicated to this sector.*
Central, mixed, and no-recycle sewage system	*Affect fate of P in sewage waste*	*We have a legacy of centralized sewage (some pipes are over 100 years old), primary wastewater treatment plant started construction in the 1970's but only completed in the 1990's. The city itself and most of the East island is mixed but the west-island does have separate wastewater and rainwater systems. Currently the pant complies with P discharge laws but there is still a significant amount of P discharged.*
Landfilling of most organic waste (w/small composting projects)	Means little P is recycled, and most accumulates in landfill sites	Have implemented a few pilot projects for organic waste collection but currently garbage collection is mixed (organic and non-organic) and sent to landfill (including all biosolids from the wastewater treatment plant). Only 11% of Montreal's solid waste is composted or diverted from landfills.
"NIMBYism" about large scale composting	Delay the implementation of composting programs and make it difficult to find sites to process organic waste, and thus P recycling	City has had political, business, and citizen opposition to two (Saint-Michel and Dorval Airport) of the four proposed processing sites necessary to implement

Factors	Importance of factor to urban P recycling	Specific Montreal situation
		100% composting program. Also some reticence from boroughs to start separate organic waste collection.
Waterway characteristics (no eutrophication around Mtl)	*Possibly less motivation to be particularly efficient and careful about P management*	*There are high P concentrations in the St-Lawrence downstream of Mtl but don't see effects directly around the city (Environment Canada 2013b)*
Diet	*Affects amount of P in food imported, produced, and P in human solid and liquid waste streams.*	
Understanding of proper collection and composting	A lack of knowledge can decrease adoption of composting and thus P recycling, and/or the creation of useable compost and thus P recycling	There seems to be a lack of knowledge in many parts of the population.
Compost Market	Determines if P is actually recycled toward food (or other) production	Currently have limited markets for the planned compost produced by the City. At smaller scales compost producers are the compost users, creating a "closed" market.
Density	Population influences amount of food consumed and wasted, and thus quantities of P imported and wasted, area determines the amount of space available for composting.	3935.7 people per km^2 in 2011 (Satistics Canada 2013), leaving limited space for home composting in the downtown core, and also limited spaces for large scale compost facilities.
Perception of actors roles and responsibilities	If stakeholders have different opinions and understandings of who should be responsible for certain aspects of P recycling or some actors not trust that an actor fulfill their roles, this can be a road-block towards increasing P recycling through compost production.	The central City (agglomeration) is responsible for organic waste treatment though the waste management plan, boroughs are responsible for waste collection for residences with less than 8 units and small businesses, but large condos, institutions, and businesses must use private contractors. There are different opinions about who and how compost should be produced (small scale vs large scale). There is also some mistrust with regards to government management because of a history of corruption (Radio-Canada 2014, Vérificateur général de la Ville de Montréal 2013)
Urban agriculture level		
Amount of urban agricultural and urban food system initiatives	Amount of UA affects the amount of P that is applied and can be recycled and the # of actors involved in urban food system initiatives can affect the amount of UA but also support policies and practices to increase UA and/or composting.	Metson and Bennett (in reivew) surveyed 163 actors, the agriculturemontreal website identified 410 gardens, and OCPM got 1500 participants and 103 "memoires", which resulted in the creation of a permanent committee on UA, GTAU got 29000 signatures to get the public consultation, there are also new overarching organizations like Food Justice Montreal (JAM), and the adoption of The Montreal Food System Plan (SAM 2025)

Factors	Importance of factor to urban P recycling	Specific Montreal situation
Understanding of larger environmental and social problems in the food and/or waste system	Can act as a motivator toward composting and the selection of specific fertilization and waste management practices, thus affecting P application and reuse, and affect the type of infrastructure put in place to compost	
Desire for education and outreach	Influences which type of P inputs gardeners and farmers will choose, the type of substrate, and waste management techniques they may choose.	Health and safety guidelines in schools, and general concern for food safety when education is a priority in UA projects often means organizers want certified inputs, and may not be able to compost on site.
Desire for "organic"	Influences which type of P inputs gardeners and farmers will choose, the type of substrate, and waste management techniques they may choose.	Access to fresh and local foods, and environmental concerns (including wanting organic) were two of the top three functions of UA community and private gardeners identified as key to their participation in Montreal (Duchemin 2013).
Access to capital for food	This affects food choices and thus P consumption and imports to the city, but also possible participation in UA to supplement food	-Food insecurity is present in 16.2% of population (Ville de Montréal 2013b) - 18% of community garden respondents indicated that food security was a motivation for UA (Duchemin 2013)
Concern about soil quality	*Impacts where UA and composting can be done on soil and where soil remediation is necessary or container gardening becomes necessary (although some studies have shown limited health risk (McBride et al., 1997)*	*There are UA sites with some heavy metal contamination (some remediation has been done, or containers provided) and study shows that not a large health risk, although people do perceive it as a large problem (Beausoleil and Price 2010, Direction de la santé publique de Montréal 2008, Wegmuller and Duchemi, 2010)*
Substrate use	*Inputs used and management can be a bit different between different types of substrate (e.g. some container garden systems have specific soil mixtures proposed, and roof gardens must use light substrate because of weight)*	*Currently more UA is on soil, whereon soil is favored on the West Island, container gardens are more common in the city-center, and there are a few roof-top gardens and farms. High density means there is a maximum area to increase UA upon, especially on soil. Large rooftop gardens, like Lufa Farms, may be one option to further expand UA but may not be able to reuse City compost because of its weight.*
Quebec laws on Environmental quality and agriculture & Quebec law on water quality	*Determines fertilizer and waste management practices on large farms, wastewater and sewage treatment techniques to meet standards*	*-Must have P balance on farm based on soil test if you have a large enough farm with animals (so must export extra manure if your soil is saturated)* *-Phosphorus in water bodies can not exceed 0.03 mg* $P*l^{-1}$

Factors	Importance of factor to urban P recycling	Specific Montreal situation
Choice of inputs and amounts (including fertilizer purchase, and availability of inputs)	Affects the amount of P applied to soil and the choices also affect the source of the P applied (recycled on or imported to the island)	Many gardeners chose to use some on-island compost, but not necessarily in large quantities and most of them supplement with bought sources of P that come from outside the island
Rules in community gardens and UA	*Affects the types of crops grown and thus how much P is applied and harvested. The fact that few animals are allowed means that there is less P flowing in and out of UA, perhaps limiting P losses, but can also limit recycling potential. Laws on compost location also limit recycling of P.*	*-No farm animals (expect west-island ag zoning)* *-plant diversity in community gardens (min 5 plants not covering more than 25% of space each)* *-cleanliness laws (can't have anything that doesn't look "orderly")*
Knowledge of proper composting (often limited)	Lack of knowledge can translate to lack of participation in composting activities, or compost not being usable when produced on-site because of contamination or not decomposing rapidly enough, implicit in the big NIMBYism about compost	UA practitioners seem more knowledgeable that non-practitioner citizens, but even in those UA practitioners that compost, some times contamination, incomplete decomposition, or poor management of ratios of input materials make it unusable.
Access to capital for UA projects (often limited)	Affects the amount of UA on the island as well as the number of trained people who can help ensure continued composting and knowledge transfer.	There is limited access to long-term and stable financial and human resources for UA. For example, there are less and less horticultural councilors in community gardens and full-time employees on NGO UA projects.
Impervious surface cover	*Affects P runoff rates from gardens and lawns. Also can affect substrate use because to cultivate on soil need access to it, so if impervious surface is high may use alternative substrate or not cultivate.*	*Areas with more impervious surface are responsible for more P losses. There is more impervious surface downtown, where there is thus less access to easy land for UA or compost sites.*
Land ownership/tenure	*Can influence what you can and are willing to do with the property and also the longevity of projects and return on investment (Brown and Carter, 2003, Lynch et al., 2001), some argue that insecure land tenure is problematic, while others argue that UA can take advantage of under-utilized spaces without long-term tenure (Smit and Nasr, 1992)*	*Less than 50% own in the city of Montreal, while over 80% of households in the West island are owned by an occupant of the household (Statistiques Canada 2013).*
Amount of different types of land use	*Relevant as it determines which actors have access to space for UA and composting. Amount of residential land use is particularly important as it determines space for private citizens which produce the most about of organic waste and highest demand for food.*	*-Residential land use is 37% on the island (including high, medium, and high density).* *-Green space is 12% (including cemeteries, gold, urban and regional parks, nature reserves, and rural land uses)* *- Vacant land is 14.57%* *(Communuaté Urbaine de Montréal 1996)*
Access to fresh water (unlimited)	*In other cities, high cost of urban water can limit*	*Montreal does not meter household water use although*

Factors	Importance of factor to urban P recycling	Specific Montreal situation
	UA projects (also when fresh water access is limited the use of wastewater (high in nutrients) can more easily be proposed in UA (Smit and Nasr, 1992)	*does have rules regulating outdoor use in the city itself*
Crop choice	*Link between P applied and how much is P harvested as different crops require different amount of P*	
Sunlight hours	*Affects crop choice and number of rotations possible and thus amount of inputs used and waste produced*	*2015.2 sunlight hours, Canada is in Plant Hardiness Zone 5a (which is enough to grow corn and most other crops) (Environment Canada 2013a, Agriculture and Agri-Food Canada 2013)*
"Short" growing season	*Affects crop choice and number of rotations possible and thus amount of inputs used and waste produced*	*156 days, (143 days or 20 weeks) Average based on survey (2013)(environ Canada 1950-1980) and survey*
High temperature and precipitation variability and average low temperature	*Affects crop choice and number of rotations possible and thus amount of inputs used and waste produced*	*-Average temperature (C°, 2012) and average growing season temp (May-Oct): 8.5 (18.26)* *-Minimum temperature (C°, 2012): -24.1* *-Maximum temperature (C°, 2012): 33.3* *-Total precipitation (mm, 2012): 927.4* *-725.8 mm rain and 192.4cm snow (Environment Canada 2013c)*
Needs to overcome barriers towards more P recycling in City and UA		
Knowledgeable citizens	Affects capacity to compost and thus recycle P properly in large quantities at individual and collective scales	
Valued compost product	Can motivate compost collection, processing, and use of recycle P if it is viewed as a valuable resource	
Ease of practice through infrastructure	Affects capacity of individuals and groups to actually recycle waste	
Monitoring	Necessary to see if implementation of any plan to increase compost and/or UA is effective, and also necessary to ensure high quality compost and trust between actors	
High compost quality (shared definition)	Need "high quality" compost to ensure P is actually reused, and need shared definition of what quality means	

5.8 Supplemental Information

5.8.1 Methods

Interview scripts

Interview Facilitators and barriers to composting in Montreal

Date:
Name of respondent (and organization):

1.What do you view as facilitators and motivators to composting in Montreal?

prompts:

1. Are there factors/elements motivate you to compost or use compost (including vermicompost, city compost, homemade compost, organization compost, BRF, leave residues on soil)?
2. Are there things Montreal, your neighborhood, or your house that make it easier to compost?

2.What do you view as barriers to composting in Montreal?

prompts:

1. Are there factors/elements that deter you or make you not want to compost or use certain types of compost?
2. Are there factors/elements/conditions that you think are stopping Montreal as a city, your neighborhood, or you from composting or reusing waste more?

Additional prompts:

1. What role do you think UA could play in composting, if any?
2. Do you think the city of Montreal has a role to play? (how do you feel with the UA Committee, SAM, and central city composting plan and facilities location?)
3. What do you consider motivators for your participation in gardening, and agricultural and food production?
4. What do you consider barriers for your participation in in gardening, and agricultural and food production?
5. What do you consider the reasons why solid organic waste is managed in this way?
6. What do you consider benefits for how solid waste is currently managed?
7. What do you consider drawback or problems with the way solid waste is managed?
8. What are barriers to changing how solid waste is managed?

FRANÇAIS

1.Y a-t-il des facteurs/éléments, que vous estimez, facilitent, ou motivent, le compostage à Montréal ? Si oui quels sont-ils?

Suivit/piste :

1. Y at-il des facteurs / éléments qui vous motive a composter et utiliser du compost (y compris le lombricompost,compost de la ville compost maison, compost collectif, BRF, ou laisser des résidus sur le sol)?
2. Y at-il des choses à Montréal, dans votre quartier ou dans votre maison qui font qu'il est plus facile de composter?

2. Y a-t-il des facteurs/éléments, que vous estimez, dissuadent, ou rendent difficile, le compostage ou l'utilisation du compost à Montréal? Si oui quels sont-ils?

Suivit/piste :
1 . Y at-il des facteurs / éléments qui vous dissuadent de composter, ou d'utiliser du compost en général ou de type particulier ?
2 . Y at-il des facteurs / éléments / conditions que vous pensez empêche Montréal en tant que ville , votre quartier , ou vous a la maison de composter et de recycler les déchets de façons plus importantes?

Autres:
1 . Quel rôle pensez-vous que l'agriculture urbaine pourrait jouer dans le compostage, s'il y en a un?
2 . Pensez-vous que la ville de Montréal a un rôle à jouer? (Comment vous sentez- vous par rapport au comité permanent sur l'AU de la Ville, le plan SAM , et le plan de la la ville pour le compostage centraliser et l'emplacement des installations?)
4 . Qu'est-ce que vous considérez comme votre motivation pour votre participation dans le jardinage , et la production agricole et alimentaire?
5 . Qu'est-ce que vous considérez comme des obstacles à votre participation dans le jardinage , et la production agricole et alimentaire ?
6 . Que considérez-vous comme les raisons pour lesquelles les déchets organiques solides sont gérés de la façon dont ils le sont en ce moment?
7 . Qu'est-ce que vous considérez comme les avantages de cette gestion des déchets organiques/solides ?
8 . Que considérez-vous sont les problèmes ou les désavantages de cette gestion des déchets organiques ?
9 . Quels sont les obstacles pour changer la façon dont les déchets organiques sont gérés ?

Ethics approval

McGill University Research Ethical Board approved the protocol for administering the interview questions, the interview questions, and data management and storage protocols (REB File # 995-0213), which were an addition to the survey questions posed within the context of research in Metson and Bennett (in review). Following is a copy of the amendment to the protocol to include the interview questions.

MCGILL UNIVERSITY
FACULTY OF AGRICULTURAL AND ENVIRONMENTAL SCIENCES

ETHICS REVIEW
AMENDMENT REQUEST

This form can be used to submit any changes/updates to be made to your currently approved research project. Explain what these changes are, and attach any relevant documentation that has been revised. Significant changes that have ethical implications must be reviewed and approved by the REB before they can be implemented.

REB File #: 995-0213
Project Title: The importance of urban agriculture in urban phosphorus cycling.
Principal Investigator: Geneviève Metson
Department/Phone/Email: Natural Resource Science/438-823-2027/genevieve.metson@mail.mcgill.ca
Faculty Supervisor (for student PI): Elena Bennett

Amendment Description: We would like to add two more open-ended questions to our survey in order to glean a better understanding of the context within which phosphorus cycling and recycling is happening in Montreal and urban agriculture, and ask permission to record responses for these two questions. We have attached a revised consent form and the two additional questions are indicated below this paragraph. We are requesting permission to record the answers as the questions are open-ended and transcription will be necessary for analysis. This addition to the survey will only be for Genevieve Metson's and Elena Bennett's use, and will not be part of the collaboration with UQAM. The recording, transcription, and notes from these questions will thus only be available to Genevieve Metson and Elena Bennett. The same procedure for confidentiality and record storage as outlined in the original proposal will be followed. The new consent form reflects these changes (and we have highlighted the changes made).

Questions:

1. What do you view as facilitators and motivators to composting in Montreal?
2. What do you view as barriers to composting in Montreal?

Principal Investigator Signature: [signature] Date: May 7th 2014

Faculty Supervisor Signature: [signature] Date: May 7th 2014
(for student PI)

For Administrative Use	**REB:** X AGR ___ EDU ___ REB-I ___ REB-II

X Expedited Review ___ Full Review

X This amendment request has been approved.

Signature of REB Chair/ designate: [signature]

Date: June 11, 2014

Submit signed original to the Macdonald Research Office, Raymond Building, Room R3-032a; Fax: 398-8732 or lynn.murphy@mcgill.ca. Electronic submissions with scanned signatures are accepted but must come from the PI's McGill email.

(August 2011)

5.8.2 Results

SI Table 1. Occurrence of themes related to facilitators and barriers to current and future composting in Montreal in each interview. Interview codes are on the y-axis and interview themes are on the x-axis where **bold** themes indicate that there are subthemes (and these subthemes follow in *italic*). The total at the bottom of each column indicates the total number of times a theme occurred and the total at the end of each row indicates the number of times all themes combine were applied to an interview.

Interview Codes	Compost Processing/ Production	Compost Quality	Compost Use	Data & Monitoring	Ease/Habit	Knowledge Integration	Laws & Rules	Negatives Of Landfills	Organic Matter Collection	**Perceptions of Organic Waste**	*Pollutant (Negative)*	*Resource (Positive)*	Political Priorities/ Will	**Roles & Responsibilities Of Actors**	*Boroughs*	*Environmental Organizations*	*Individual citizens*	*Private Companies*	*Trust*	*Central Government*	Space/ Density	Urban Agriculture As A Catalyst	Total
i1	7	17	4		3	3		2	5	2	1	1		12		1	4	5		3	1		72
i2					5	2	1	1	16	5	4	2		5			2			3	3	1	50
i3	5		1		10	8	2		10	9	5	4		8	2	6	1			1	3		76
i4	7		3			3	1		1	1	1	1		4	1	1	3				1	1	31
i5	4	4	8	2	6	10	1		2	6	3	3	1	14	5	4	1	1	2	6	2	2	89
i6	4	1	1		1	3				1		1		2		1				2	2	1	20
i7	3	1	1		3	5			1	1	1			7	1	3	1			3	1		32
i8	7	6	4	4	7	5	3		6	3	2	1	2	12	3	1	3	1		6	1		78
i9	10	2	2		8	4		1	5	3	1	2	1	5	1	2	4	1		4	4	3	63
i10		1	2		10		2		1					2							1		19
i11	5	1	2	2	1	4		1		2	1	1		3				1		3	4		31
i12 & i13	9	2	2		1		3		7	3	2	2	1	10	2					10	4		58
i14	6		3	1	1	3	1		1	3	1	2		11		2	2	2	1	6	1	2	50
i15	5	5	9	1	2	3	2	2		6	2	4	2	15	1		7			10	7		83
i16	9	3	2	2	3	5		1	6	6	2	4	3	9	1	4	4	2		5	2	2	75
i17	6	3	1		4	3				2	1	2		6	2	4	3			1	2		41
i18	7	3	4	3	2	9			5	1		1		8	1	2	1		2	5	1	2	57
i19	3	5	3	2	4	1		1	2	8	5	6	1	6	2	1		1	1	1	4	2	60
Total	97	54	52	17	71	71	16	9	68	62	32	37	11	139	22	32	36	14	6	69	44	16	

SI Table 2. Co-occurrence of themes related to facilitators and barriers to current and future composting in Montreal. **Bold** themes indicate that there are subthemes (and these subthemes follow in *italic*). Each cell indicates where an interview passage was coded for the two themes intersecting at that cell. The total at the bottom of each column and each row indicates the total number of times a theme occurred with any of the other themes.

	Compost Processing/ Production	Compost Quality	Compost Use	Data & Monitoring	Ease/Habit	Knowledge Integration	Laws & Rules	Negatives Of Landfills	Organic Matter Collection	**Perceptions of Organic Waste**	*Pollutant (Negative)*	*Resource (Positive)*	Political Priorities/ Will	**Roles & Responsibilities Of Actors**	*Boroughs*	*Environmental Organizations*	*Individual citizens*	*Private Companies*	*Trust*	*Central Government*	Space/ Density	Urban Agriculture As A Catalyst	Total
Compost Processing/ Production		23	28	3	15	18	4	1	14	16	7	11	2	58	9	19	28	3	1	22	23	3	313
Compost Quality	23		24	2	2	8		3	8	4	1	4		36	7	8	12	6	1	17	9	2	180
Compost Use	28	24		3	7	8	1	1	5	10		10	2	27	4	6	12	1	3	11	9	8	184
Data & Monitoring	3	2	3		1	2	3		3				1	8	2			3	2	5			38
Ease/Habit	15	2	7	1		15	2		27	11	8	4	1	24	1	9	8		1	9	10	2	158
Knowledge Integration	18	8	8	2	15		2	2	12	16	8	8		33	3	16	10	2		11	1	5	181
Laws & Rules	4		1	3	2	2			6	1		1	2	7	1			1		7	5		43
Negatives Of Landfills	1	3	1			2			3	4	2	3		3			1	1		2	1		27
Organic Matter Collection	14	8	5	3	27	12	6	3		13	10	4	3	36	11	3	8	6		22	10		204
Perceptions of Organic Waste	16	4	10		11	16	1	4	13		34	40	3	16	1	4	6	1		6	8	5	203
Pollutant (Negative)	7	1			8	8		2	10	34		7		5		1	1			2	4		92
Resource (Positive)	11	4	10		4	8	1	3	4	40	7		3	13	1	3	5	1		5	4	5	135
Political Priorities/ Will	2		2	1	1		2		3	3		3		7	3					7	2		36
Roles & Responsibilities Of Actors	58	36	27	8	24	33	7	3	36	16	5	13	7		24	34	41	14	6	69	20	7	493
Boroughs	9	7	4	2	1	3	1		11	1		1	3	24		6	6	2		8	4		94
Environmental Organizations	19	8	6		9	16			3	4	1	3		34	6		9	2		6	4	2	133
Individual citizens	28	12	12		8	10		1	8	6	1	5		41	6	9		3		9	10	2	174
Private Companies	3	6	1	3		2	1	1	6	1		1		14	2	2	3		1	3			50
Trust	1	1	3	2	1									6				1		2			18
Central Government	22	17	11	5	9	11	7	2	22	6	2	5	7	69	8	6	9	3	2		10	5	239
Space/ Density	23	9	9		10	1	5	1	10	8	4	4	2	20	4	4	10			10			135
Urban Agriculture As A Catalyst	3	2	8		2	5				5		5		7		2	2			5			48
Total	313	180	184	38	158	181	43	27	204	203	92	135	36	493	94	133	174	50	18	239	135	48	

6 CONCLUSION

6.1 Contributions to knowledge

Sustainable P management will become a more pressing and critical issue for food security and aquatic pollution as global population increases, food demand increases and the types of foods demanded shift to require more P inputs (Van Vuuren et al. 2010). Global mineral P reserves are decreasing and becoming more geopolitically concentrated as reserves in some countries are completely consumed, causing the price of fertilizer to increase, decreasing farmers' access, and increasing the price of food (Cooper et al. 2011, Cordell and White 2011). Without changes in how we manage P throughout our food system, increased P consumption may also increase the risk of P loading in sensitive aquatic ecosystems from agricultural and urban ecosystems alike (Tilman et al. 2001, Van Drecht et al. 2009).

Although the P problem at the global scale is clear, implementing solutions at national, regional, and local scales remains a challenge, as people and places are not all equally affected by the P challenge, or have the same capacities to alter P management (Cordell and Neset 2014). As large consumers of P, and drivers of P use and waste globally, developing countries, and particularly cities in developed countries, have a key role in shaping future P cycling (Weikard and Seyhan 2008). However, for cities of the Global North to act as "bright spots" of good practice instead of simply "hotspots" of P cycling, we need to have a better understanding of city-specific P cycling, including the social, ecological, and technological drivers of urban P cycling, and the capacity for P management solutions to address both P challenges and other local sustainability goals.

This thesis contributes to filling these critical research gaps through two means: 1) Quantifying and qualifying the role of two understudied solutions: dietary choices (Chapter 2), and urban agriculture (UA, Chapters 3 & 5), and 2) developing and applying a way to more fully integrate local socio-ecological context (i.e., social, ecological, and technological drivers) into the study of urban P, a key ecosystem in the anthropogenic P cycle (Chapters 3, 4 & 5). The overall objective in filling these research gaps was to increase our understanding of P management in a way that ensures that this understanding can be used to create real-world change.

First, I focus on the role of human diet in the global demand for mined P, examining diet mitigation as a way to decrease both demand for mined P and runoff to aquatic ecosystems. Past estimates of the importance of human diet in P sustainability only considered rough categories of diet (e.g., vegetarian vs. meat consumption, or developed vs. developing countries). Additionally, those studies used a weak proxy for P consumed: the percentage of P consumed that is found in excreta along with data on P in sewage. Chapter 2 improves upon past estimates of the relationship between diet and P demand in several ways: 1) I calculated the P required to produce all food crops rather than relying on estimated human excreta as a proxy for P in food consumption. This means my calculations are not reliant on broad estimates of waste through the food system like previous studies (e.g., Cordell et al. (2009a), Cordell et al. (2009b), Smit et al. (2009), Schroder et al. (2010)), but instead rely on a more direct measurement. 2) My comprehensive approach has also permitted the first systematic comparison of national requirements for P to produce food as well as analysis of the impact of specific food groups on the overall dietary P footprint. Although the scale of analysis here was global and national, the idea of incorporating context (spatial and temporal) and drivers was present, and the results are relevant for cities around the world. As consumption centers, urban ecosystems – and the dietary choices of their residents – are key components of the human P cycle.

Next, I focus on one city, Montreal, Canada, as a case study and quantitatively examine the P flows of the city's food system and urban agriculture system. Although the link between UA and P recycling has been studied in the developing world (e.g., Gumbo et al. (2002), Meinzinger et al. (2009)), Chapter 3 is the first to use site-specific information (data collected through surveys) to quantitatively examine P cycling in UA, and to further contextualize it within the larger food and waste system of the city, in the developed world. I find that in Montreal, most P entering the food system ultimately ends up in landfills, as little P is recycled though composting of food and green waste, and biosolids are incinerated and landfilled. UA currently plays only a small quantitative role in Montreal's P cycling, and does not have the capacity to recycle all the P waste produced by such a large and highly concentrated population. However, P recycling is much higher within the UA system than the island as a whole, and as such UA may have potential as a catalyst to broader scale recycling in the city. Understanding this potential however required a more nuanced understanding of drivers of P cycling, and how these drivers may be acting as facilitators or barriers to increase P efficiency and recycling in the city.

I then create a framework to allow urban P cycling researchers to better integrate locally relevant driving factors to their studies to make them more relevant to urban decision-makers (Chapter 4). The urban SFA literature widely acknowledges that, although P SFA studies are critical, their results are often not sufficient to instigate changes in policy and P management. However, there remains a lack of guidance on how to make urban P SFA studies more relevant to decision-makers. I review the urban P SFA and system thinking literature and identify eight categories of social, ecological, and technological driving factors. I demonstrate how identifying and understanding locally specific factors and their relationship to one another through system thinking can contribute to more stakeholder relevant urban P sustainability research. Through this framework, I suggest a way to identify synergies with existing goals to start a meaningful dialog with urban decision-makers.

Finally, I empirically test this framework by refocusing on the Montreal case study. I examine the driving factors of P cycling and recycling in the city and in UA, in order to identify barriers and facilitators to increasing P recycling in Montreal, and explore the role UA may play (Chapter 5). I find that the current municipal organic waste recycling policy should facilitate P recycling but there are social and infrastructure barriers to implementing the plan, including cultural perceptions of waste, lack of knowledge and trust, and different perceptions about compost production and quality. Focusing on UA, which has gained increasing public support, could allow the city to overcome these barriers, especially if UA and municipal partners can develop a shared definition of “high quality” compost, building social capital in the process. As I describe in Chapter 4, SFA studies often suggest future solutions and possible struggles in implementing them, but rarely follow-up with site-specific research to understand the social and/or ecological context that affects the relevance of suggestions. In Chapter 5 I provide a case study example of how such a contextual understanding can start to be built as I identify locally relevant ways of overcoming barriers to increasing P recycling, and do so by building on Chapter 3.

I use an interdisciplinary approach throughout this thesis to tackle the complex nature of P sustainability. Although integrating across natural and social science methods is often cited as being an essential component of studying socio-ecological systems, especially urban systems (Grimm et al. 2000, Collins et al. 2010), and a necessary component to tackling complex sustainability problems (Miller et al. 2008), including P (Metson et al. 2013), this can be difficult to do and not often systematically embraced or carried-out (Alberti 2008). In addition to their empirical contribution to knowlege Chapters 3 (using SFA) and 5 (using interviews, participant observation, and document review) represent a step forward in integrating diverse methodologies to address a sustainability challenge. I use diverse methods to quantify and qualify urban P cycling and the context that surrounds it in order to increase our understanding of P cycling in a way that may make it easier to engage with decision-makers and consider P management from a systemic perspective.

As a whole, this thesis contributes to the newly emerging field of P sustainability research. Scientists have separately focused on the human alteration of the P cycle (e.g., Smil (2000)), physical and economic scarcity (e.g., Ulrich and Frossard (2014)), agronomy (e.g., Iyamuremye and Dick (1996)), and pollution (e.g., Smith and Schindler (2009)) challenges for quite some time, contributing key knowledge necessary to better manage the resource. Since Cordell's (2009a) paper on the global challenges to better managing this essential element, research combining multiple perspectives, disciplines, and scales on solutions and solution implementation has increased exponentially (Ulrich and Schnug 2013). However, although cities had been studied in the context of urban metabolism and local resource management, or globally due to their waste management and P recycling potential (e.g., Weikard and Seyhan (2008), Troschinetz and Mihelcic (2009), Mihelcic et al. (2011)), cities had not yet been fully considered for their local and global potential to simultaneously address issues of P scarcity and P pollution, or as catalysts for broader scale change. Here, I bring this potential to the forefront in a way that is relevant to decision-makers, and that integrates the transdiciplinary research requirements of the P sustainability challenge.

6.2 Future Directions

6.2.1 Empirical understanding of urban P cycling

While urban nutrient cycling studies have increased dramatically in recent years, key gaps remain. To improve environmental management of cities, including P management, we require long-term and consistent collection of quantitative data in and across urban ecosystems. More data-collection (including soil, atmospheric, and water sampling) is needed to quantify material flows and possible environmental concerns associated with the flow of these materials (Wortman and Lovell 2013), as well as the relationship between biogeochemical cycles and ecosystem services (Pataki et al. 2011). In this thesis for example, I was not able to quantify losses through runoff and erosion in Chapter 3 due to lack of data. In fact, site-specific monitoring data would increase the accuracy of all P stock and flow measurements in Montreal. Although still very useful, using data from other cities, provincial and national data sets, and making assumptions about P flow relationships inserts some level error, uncertainty, and bias in results. My research reiterates the need for continued and geographically diverse social and biophysical data collection for scientists and policy-makers to get an accurate picture of current urban ecosystem functioning, but perhaps more importantly to monitor the effects of changes in driving factors (including policies) over time in order to create reflexive management policies to meet sustainability goals (Cundill and Fabricius 2009).

6.2.2 Cross-city comparisons and multi-scale work

A natural and necessary extension of the Montreal case study work (Chapters 3 & 5) is conducting cross-city comparisons of P cycling and the role of UA. By doing so, we would gain a better understanding of which variables drive or control the current role UA plays in urban P cycling and how much these drivers vary by city (contributing to the refinement of the framework developed in Chapter 4). Cities with similar biophysical and social contexts may then be able to better learn from one another to maximize the benefits and minimize costs associated with UA and sustainable P management. In order to do so, it will be necessary to explicitly study UA and urban P cycling in a quantitative way. Currently most UA work focuses on social components and does not consider P explicitly and urban P budgets often use regional or national averages to quantify the role of UA if they consider UA at all, making the need for long-term and standardized monitoring even more apparent.

6.2.3 Participatory future scenarios and models

One of the main objectives of my thesis work, and P sustainability literature in general, is to create a better understanding of problems and solutions that will yield real world changes. As such, a critical next step in urban P sustainability research is engaging with practitioners. Chapters 2 and 4 make considerable advances in making existing quantitative knowledge more decision-maker relevant by explicitly considering the context around P cycling, making it possible to identify synergies with existing urban priorities, and explore the facilitators and barriers that may exist toward P sustainability. Collaboration between practitioners and multidisciplinary scientists is necessary to tackle complex sustainability issues such as P management (Kates et al. 2001). Engaging in transdiciplinary research (Lang et al. 2012), including participatory future visioning and quantitative system dynamic models to help select solutions, may be a way to move from theory to practice.

To improve P sustainability, we must weigh decisions about each potential P management strategy in relation to other societal and environmental priorities (Neset and Cordell 2012). Local, regional, and global contexts thus become important factors in the creation of targeted P-management plans that take into consideration multiple priorities and realities at different scales. Ultimately, the decision-making mechanisms, priorities, and perceptions of actors are essential to understanding these connected priorities. As such, engaging in co-generated research may be key for research results to be relevant and used to change P management. Creating future visions is one way to engage in such a process, focusing on creating a shared vision of a desirable future and back-tracking to use both quantitative and qualitative data about the system to create a management plan(s) to attain this vision (Vidal 2006, Iwaniec 2013). System dynamic models may aid in exploring possible future scenarios and creating implementation plans tailored to the context of particular cities. There is currently no systematic method or model for quantifying the importance of available P management options, and how each strategy will be affected by the system of locally-relevant social, ecological, and technological drivers. Creating such a model would directly build on the qualitative framework developed in Chapter 2 and work done by

Cordell et al. (2011) (as well as complementing efforts of assessing, modeling, and visioning P sustainability at global and national scales (Cordell et al. 2009b, Cordell and Neset 2014)).

6.3 Overall conclusions

In this thesis, I have demonstrated how dietary choices and UA can transform P cycling, and shown that we need to systemically integrate social, ecological, and technological driving factors into urban nutrient research to tailor solutions to the context in which problems occur. I have shown the relevance of integrating local context into the study of urban P through literature review and the development of a framework (Chapter 4), and an empirical case study (Chapters 3 & 5) that applies this framework. I have helped demonstrate how UA (Chapters 3 & 5), and dietary choices (Chapter 2) can contribute to decreasing mined P demand, and how their current and future role in P management is dependent on social context at many scales. However, sustainable P management remains a multi-scalar challenge and using these findings to change local P management, in the context of a complex global challenge, requires further research. Key future endeavors include better collection of long-term and spatially explicit data to ensure an accurate understanding of urban P dynamics, cross-city comparisons to better develop theories around typologies of cities that can learn from each other, and participatory research with decision-makers to co-create P management plans that get implemented.

P management is a pressing and complex sustainability challenge, and research about P sustainability increasingly demands transdiciplinary approaches (Ulrich and Schnug 2013). In addition, the pressing nature of the challenge means that scientists must increasingly work with policymakers and other stakeholders to develop research that can help cities face the P challenge in an informed fashion. Research that can effectively bridge gaps between how different disciplines conceptualize and study P challenges and solutions, and how researchers and decision-makers understand risk and change, is critical. This thesis embodies an effort to balance these multiple objectives. To do so, it draws upon different methodologies and perspectives (from the physical and social sciences) to understand P cycling in a way that is more relevant to urban decision-makers. The research is quantitative, explicitly considers the social, ecological, and technological drivers of P cycling to identify synergies with existing policy priorities, and locally-relevant barriers, and focuses on a critical ecosystem of P management: cities.

6.4 References

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