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Phosphorus in Phoenix: a budget and spatial representation of phosphorus in an urban ecosystem

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Abstract. As urban environments dominate the landscape, we need to examine how limiting nutrients such as phosphorus (P) cycle in these novel ecosystems. Sustainable management of P resources is necessary to ensure global food security and to minimize freshwater pollution. We used a spatially explicit budget to quantify the pools and fluxes of P in the Greater Phoenix Area in Arizona, USA, using the boundaries of the Central Arizona–Phoenix Long-Term Ecological Research site. Inputs were dominated by direct imports of food and fertilizer for local agriculture, while most outputs were small, including water, crops, and material destined for recycling. Internally, fluxes were dominated by transfers of food and feed from local agriculture and the recycling of human and animal excretion. Spatial correction of P dynamics across the city showed that human density and associated infrastructure, especially asphalt, dominated the distribution of P pools across the landscape. Phosphorus fluxes were dominated by agricultural production, with agricultural soils accumulating P.

Human features (infrastructure, technology, and waste management decisions) and biophysical characteristics (soil properties, water fluxes, and storage) mediated P dynamics in Phoenix. P cycling was most notably affected by water management practices that conserve and recycle water, preventing the loss of waterborne P from the ecosystem. P is not intentionally managed, and as a result, changes in land use and demographics, particularly increased urbanization and declining agriculture, may lead to increased losses of P from this system. We suggest that city managers should minimize cross-boundary fluxes of P to the city. Reduced P fluxes may be accomplished through more efficient recycling of waste, therefore decreasing dependence on external nonrenewable P resources and minimizing aquatic pollution. Our spatial approach and consideration of both pools and fluxes across a heterogeneous urban ecosystem increases the utility of nutrient budgets for city managers. Our budget explicitly links processes that affect P cycling across space with the management of other resources (e.g., water). A holistic management strategy that deliberately couples the management of P and other resources should be a priority for cities in achieving urban sustainability.

Key words: biogeochemistry; nutrient budget; Phoenix, Arizona, USA; phosphorus; sustainability; urban; urban ecosystem.

INTRODUCTION

Phosphorus (P) is essential for all life and is often a limiting nutrient to many ecosystem processes (Chapin et al. 2002). By far, the largest P reserves lie within the Earth's crust. Within the biosphere, P is cycled among living and nonliving components of ecosystems, and eventually is transferred to the ocean. Most unaltered ecosystems tightly cycle P, but humans have significantly

accelerated local and global P cycling by mining geologic P reserves for fertilizer manufacture and use (Cordell et al. 2009). A significant amount of this anthropogenically cycled P is lost through erosion, runoff, and wastewater discharges (Bennett et al. 2001, Cordell et al. 2009, Childers et al. 2011), leading to eutrophication of aquatic ecosystems (Bennett et al. 2001, Smith and Schindler 2009). The United Nations has recently highlighted that sustainable P management is necessary to ensure global food security and minimize freshwater pollution (UNEP 2011). Although sustainable P management is often framed as a global problem, solutions require changes at all scales, from the local to the global, and in all parts of the P cycle, including agricultural producers and urban consumers.

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Urban ecosystems are focal to anthropogenic changes of biogeochemical cycles (Kaye et al. 2006, Grimm et al. 2008). Humans alter urban biogeochemistry by deliberately changing inputs and outputs of materials through the city (i.e., food, building material, and fuel), by altering air, water, and soil conditions, and by changing where materials accumulate. Urban biogeochemistry alters human activity by influencing city-wide policy regulations (i.e., pollution control), by influencing costs of manufacturing, agriculture, and transportation, and by affecting human health and quality of life. Although cities comprise around 7% of the terrestrial ice-free landscape globally (Ellis and Ramankutty 2008), their ecological impacts extend far beyond the boundaries of urban settlement (Folke et al. 1997, Luck et al. 2001, Foley et al. 2005). For example, concentrated populations in cities consume agricultural products that require P fertilizer and are grown primarily outside of the city (Folke et al. 1997, Luck et al. 2001). Most of this imported P is disposed of as food and human waste and concentrated in wastewater, ultimately causing P pollution and eutrophication downstream (Cordell et al. 2009, Nyenje et al. 2010). As urban populations and per capita consumption continue to grow (U.N. Population Division 2010), “upstream” urban nutrient demand and “downstream” urban P waste will continue to increase, contributing to an unsustainable human P cycle. Closing the urban P cycle will be crucial to closing the human P cycle (Childers et al. 2011). In order to close urban P cycles, we must first have a better understanding of P cycling in urban systems. In this paper we construct a holistic urban P budget to contribute to the understanding of urban ecosystem function in a way that is compatible with city managers’ decision-making needs.

Nutrients budgets are a useful accounting tool because they quantify inputs, internal fluxes, outputs, and pools in order to understand nutrient movements. Previous urban nutrient budgets suggest that, while fluxes and pools vary among nutrients, cycles are dominated by human fluxes. For example, although N retention in Bangkok is quite low (3%) and P retention is high (51% of inputs), fluxes in and out of Bangkok are primarily mediated by humans (Faerge et al. 2001). Previous urban P budgets have focused primarily on urban food systems (Faerge et al. 2001, Gumbo et al. 2002, Antikainen et al. 2008, Neset et al. 2008, Drechsel et al. 2010). More comprehensive urban P budgets have demonstrated that fluxes associated with food systems (e.g., commercial fertilizers, food imports, and human waste) dominate in cities (Nilsson 1995, Tangsubkul et al. 2005, Han et al. 2011). Beyond the effects of food systems, industrial ecology research has demonstrated the importance of nonfood materials in urban material budgets (Decker et al. 2000, Matsubae-Yokoyama et al. 2009). Most of these nonfood materials have not previously been incorporated into urban nutrient budgets, but may represent significant fluxes and pools in the system. Materials that make up the built

environment such as asphalt, wood, and cement, all of which contain substantial amounts of P, are likely to be particularly important storage pools. The social (e.g., safety regulations) and biophysical (e.g., climate) drivers that regulate P dynamics through urban food systems may differ from those for the built environment. These differences emphasize the importance of including the latter in urban nutrient studies. We include both in our Phoenix urban P budget.

Budgeting approaches are useful for identifying major fluxes as well as opportunities to reduce downstream losses and increase recycling. However, most budgets are not spatially corrected or articulate even though fluxes and pools occur over *space* and may differ in magnitude and rate across the landscape. This spatial heterogeneity can have a major impact on how nutrient pools and fluxes are managed, especially when they have transportation costs associated with them. This spatial component is especially important in urban ecosystems where sources of P output (often waste) are not always co-located with input needs. Taking into account the spatial patterns of nutrient use, production, and storage is therefore fundamental for understanding and effectively managing urban nutrient cycles. A spatial understanding of nutrient cycling could allow for more nutrient-centric urban planning, where sources and sinks are co-located to maximize recycling. We consider the spatial distribution of P pools and flows here in order to make better recommendations on the range of P management options that may be appropriate for Phoenix.

We quantified the pools and fluxes of P in the greater Phoenix metropolitan area in Arizona, USA (Fig. 1) and explored the distribution of dominant pools and fluxes of P in the landscape for the year 2005. We investigated P dynamics for the entire metropolitan region, as well as among the soil, vegetation, water, animal, and material (e.g., paper) components of the desert, urban, and agricultural subsystems that make up Phoenix. In this paper we addressed the following research questions: (1) What are the magnitudes of major fluxes and pools across the ecosystem boundary and among subsystems? (2) What is the spatial arrangement of P movement and storage in the urban ecosystem? (3) Can we link major P fluxes and pools to social, technological, and biophysical characteristics of our study system? Our synthesis of this information is framed relative to the sustainable P management at the urban ecosystem scale.

METHODS

Study area

The greater Phoenix metropolitan area, which we define here with the boundaries of the Central Arizona–Phoenix (CAP) Long-Term Ecological Research (LTER) site, is a 6400-km² region in the semiarid Sonoran Desert that includes desert and agricultural land uses, as well as the Phoenix metropolitan area, and covers 27% of Maricopa County (Fig. 1). The greater

FIG. 1. Boundaries of the Central Arizona-Phoenix Long-Term Ecological Research site (CAP) and the greater Phoenix metropolitan ecosystem within Maricopa County, Arizona, USA. The black border indicates the boundaries of the CAP system, which we used as our study area to represent the greater Phoenix metropolitan area. Agricultural, desert, recreational, urban, and water land cover are indicated in color, and the Phoenix downtown area is indicated by a dot as a reference point (Redman et al. 2005; *available online*, see footnote 13). The Indian reservation land was not included in the CAP study area.

Phoenix area has a population of ~4 million people and, despite being hard hit by the economic recession in 2005, grew 31% between 2000 and 2010 (U.S. Census Bureau, information *available online*).⁵ The majority of the study system land cover is Sonoran Desert (50%; Fig. 1), where vegetation consists mainly of shrubs and cacti. Rapid urban growth since the 1950s has replaced large agricultural and desert tracts of land with residential and other urban land uses (see Plate 1). Urban land uses account for ~25% of the 6400-km² area (Redman et al. 2005). Agricultural production has been an important part of this landscape since the first human settlements in the area several thousand years ago. In 2005, however, agriculture accounted for only 11% of land use, compared with 25% in 1955 (Knowles-Yáñez et al. 1999; the remainder of land use is accounted for by recreational areas and water).

We included in our study system the atmosphere (up to the planetary boundary layer) and the soil (down to 30 cm depth), except where asphalt covers the soil, in which case, we only considered the first 10 cm of asphalt (we did not consider where buildings cover soil). We selected these boundaries to include major soil pools of P for which adequate data exist, as well as pools in the built environment (asphalt) and fluxes of P from the atmosphere. As an arid-land city, water availability is a major concern. Water sources include three rivers (the local Salt and Verde Rivers and the distant Colorado River) and groundwater. Local resource management is often directly related to water management or constrained by existing water-allocation policy or infrastructure (Gober and Trapido-Lurie 2006).

We used a three-pronged approach to understanding P cycling in the greater Phoenix metropolitan area. First, we used a mass balance approach to estimate both human and natural fluxes of P into, from, and within the

⁵ <http://quickfacts.census.gov/qfd/states/04/04013.html>

greater Phoenix area and identified the subsystems that drive the major fluxes. Then, we estimated major pools of P in the biosphere, geosphere, and built environment. We estimated all fluxes and pools for total P, unless otherwise noted in the methods. Finally, we used land cover and land-use data to visualize these data spatially. The combination of these three approaches gave us a comprehensive picture of P dynamics in the greater Phoenix area: major fluxes of P, which materials hold the most P, and where P is located across the landscape.

Mass balance approach

We used a mass balance approach to estimate all P inputs to and outputs from the greater Phoenix area ecosystem. In addition, we divided the area into subsystems to examine internal fluxes (arrows in Fig. 2) between soil, vegetation, animals (including humans), the built environment, and water (color codes in Fig. 2). We included both natural fluxes, such as atmospheric deposition, and fluxes that are mediated by humans, such as food imports. By necessity, we represented some fluxes as net fluxes (net flux = inputs – outputs).

Comparisons of fluxes with pools can be fundamental for understanding system dynamics. While pools and fluxes are linked through changes in net fluxes, they may not be distributed evenly over the landscape. In addition, the subsystem that dominates fluxes may be different from the subsystem that dominates pools. Because we were interested in implications for sustainable P management, the locations of large pools were also important for this study. Pools may be sources of P that are recycled within the system. We estimated pools of P in soils, vegetation, animals, and the built environment. Although we were not able to estimate all possible pools of P due to data limitations (e.g., in construction materials other than asphalt), these estimates represented a more comprehensive approach to developing urban nutrient budgets.

In the following section, we describe our approach for calculating fluxes to and from each subsystem and pools of P within each subsystem. Detailed assumptions, data sources, and calculations can be found in the Supplemental Materials. We estimated fluxes using the following general equation:

$$\text{P Flux (Gg/yr)} = \text{mass of material/year} \\ \times \text{P concentration of material.} \quad (1)$$

We estimated pools using the following general equation:

$$\text{P Pool (Gg)} = \text{standing mass of material} \\ \times \text{P concentration of material.} \quad (2)$$

We computed P pools and fluxes using data from 2005, or the nearest available date. We used Phoenix-specific data for P concentrations and material pools and fluxes whenever possible. If data explicit to the Phoenix area were not available, we used the next best available data. In the rare case where no data were available, we

calculated fluxes by balancing inputs and outputs (thus assuming steady state).

Atmosphere.—Dust containing P is transported by wind from distant ecosystems (Chadwick et al. 1999, Neff et al. 2008, Field et al. 2010), representing an input to the entire Phoenix area. Both dust and particulate matter from fossil-fuel burning are also produced within the boundaries of our study area and may be redeposited within the system or carried away via wind. We used wet and dry atmospheric data from CAP long-term ecological research (Hope et al. 2004, CAP LTER 2005) to estimate total inputs of P as wet and dry atmospheric deposition (Lohse et al. 2008). Atmospheric P deposition may be highly variable from year to year depending on precipitation; our data represent a five-year average (2000–2005). We also estimated fluxes to the atmosphere via fossil-fuel burning using per capita fossil-fuel use (U.S. Energy Information Administration Independent Statistics and Analysis, data available online)⁶ and an average P concentration in gasoline emissions (Rand 2003). We assumed that dust produced within the Phoenix ecosystem was redeposited within the ecosystem (see Appendix A for more details).

Soils.—Soils receive P from atmospheric deposition, chemical fertilizers, animal and human excreta (including biosolids), wastewater, and plant litterfall. Exports from soil include plant uptake, runoff, and dust formation. We assumed that dust formation is primarily redeposited within the ecosystem and therefore represents a net zero flux. We categorized soils as mesic residential, xeric residential, nonresidential urban (industrial and commercial areas), desert, and agricultural (Kaye et al. 2008). We estimated chemical fertilizer and manure inputs to agriculture and residential soils from USGS [U.S. Geological Survey] fertilizer-use reports (Ruddy et al. 2006), assuming that the ratio of chemical fertilizer application for the greater Phoenix area was the same ratio between total harvested area in Maricopa County to the harvested area in our boundaries of the greater Phoenix area (USDA 2007). We estimated P in runoff from urban soils and other surfaces from Fossum (2001). We used areal export values from the Verde River watershed multiplied by the area of desert in our study system in order to approximate runoff from desert soils. We assumed negligible runoff from agricultural soils because fields are level, and high evaporation rates do not allow water to flow over long distances (Arizona Cooperative Extension, *personal communication*). Runoff for all land covers is highly variable based on total precipitation and the magnitude of monsoon events (Lewis and Grimm 2007). Due to data limitations we were not able to estimate storm runoff as a variable in our analysis (although we note that the CAP LTER Program is now intensively sampling stormwater runoff). We assumed that a negligible amount of P applied to surface soils (e.g., fertilizer) is transferred to

⁶ http://www.eia.doe.gov/dnav/pet/pet_cons_refmg_a_EPM0_VTR_mgalpd_a.htm

FIG. 2. Central Arizona Phoenix phosphorus budget for 2005. Central boxes are subsystem pools (e.g., soil, vegetation, animals, water). Arrows are flows into and out of the Phoenix ecosystem or between subsystems; arrows are sized relative to the magnitude of the flow and colored based on the subsystem they enter; gray arrows are small flows (<0.09 Gg P/yr); dashed arrows are unknown flows; gray dashed arrows are unknown flows that are assumed to be small.

groundwater via infiltration, because of high rates of evaporation and low rates of infiltration minimizing the movement of P with water. Pools of bioavailable P in soils were estimated using CAP LTER data per Kaye et al. (2008; see Appendix A for more details).

Water.—Water enters the Phoenix area through precipitation; surface water from the Salt, Verde, and Colorado Rivers; and groundwater, carrying with it dissolved and particulate P. Once within the greater Phoenix area ecosystem, the water is transported through extensive infrastructure for irrigation and municipal supply networks. Much of the wastewater produced by industrial and residential users is treated and then reused by agricultural and industrial sectors of the city. Stormwater runoff carries P from soils to surface water during discrete events (see the *Soils* subsection above for runoff estimation methods). Water leaves the greater Phoenix area as surface water to the Salt and Gila Rivers or is used to recharge groundwater.

We calculated water fluxes using several methods. We calculated surface water, water quality, and discharge

average annual fluxes from 2000–2005 using the midpoint method (Baker et al. 2001) using data from the USGS. For P fluxes related to internal water allocation to agricultural, residential, and industrial users, we created a water budget using water use data and water delivery data (MAG 2005). We then used water chemistry data from municipalities (City of Tempe, *personal communication*), state agencies (Arizona Department of Environmental Quality, *personal communication*), and CAP LTER research (Water Monitoring Project, information available online)⁷ to estimate P fluxes. To calculate fluxes of P in reused effluent, we used data on wastewater effluent allocation (Lauver et al. 2001), effluent P concentrations from CAP LTER research (Water Monitoring Project; see footnote 7), and biosolid allocation and P concentrations from Arizona Department of Environmental Quality (ADEQ) records from 2005 (ADEQ 2006; see Appendix A for more details).

⁷ <http://caplter.asu.edu>

Vegetation.—We divided vegetation according to the landscape type in which it is found: xeric residential, mesic residential, urban nonresidential, desert, and agriculture categories, to estimate and visualize pools and fluxes. All vegetation takes up P from the soil. For simplicity we assumed all litterfall is returned to the soil in the desert. Urban yard trimmings are sent to landfills or composted (Maricopa Association of Governments 2005), and agricultural crops are fed to livestock (dairy cows) or humans, or exported for processing (e.g., cotton).

We estimated pools and fluxes for each nonagricultural vegetation type (shrub, tree, grass, other) in the Phoenix area. We used carbon (C) flux data (net primary production, NPP) calculated for the year 2000 (Melissa McHale, North Carolina State University, *personal communication*) and P concentration data for dominant urban and desert plant species from the literature (Freeman and Humphrey 1956, Meyer and Brown 1985, Lajtha and Schlesinger 1988, Muthaiya and Felker 1997, Williams and da Silva 1997) to estimate fluxes of P through vegetation. We assumed that P uptake and litterfall were proportional to net primary productivity and that C:P of uptake and litterfall were equal to ratios of biomass for each plant type (i.e., allocation to roots, leaves, and stems of desert shrubs, trees, and grass). NPP data were not available for lawns; therefore, we assumed that lawn uptake was equal to P lost in yard trimming collection in mesic landscapes (i.e., pool was steady state). We used vegetation biomass data for the greater Phoenix area (Melissa McHale, North Carolina State University, *personal communication*) and P concentration values from the literature (Freeman and Humphrey 1956, Meyer and Brown 1985, Lajtha and Schlesinger 1988, Muthaiya and Felker 1997, Williams and da Silva 1997) to estimate pools of P in vegetation.

We estimated agricultural uptake as the amount of P in harvested crops, in addition to uptake by woody crops like citrus, which we estimated using rates of NPP. NPP data were not available for nonwoody crops, and therefore, we were not able to estimate P uptake for these crops and the return of crop residues to soils. We calculated harvest using crop production data from the U.S. Census of Agriculture for Maricopa County. We applied crop production values to the greater Phoenix metropolitan study area using the National Agricultural Statistics Service (NASS) GIS crop-cover layer from 2010 and P concentration data from the USDA-NRCS crop nutrient-removal online tool (see Appendix A for more details). P removed as harvested crops is an input to local human food supply, to feed for dairy cows, or is exported. We calculated net fluxes of agricultural products to and from the region, and thus assumed that all edible crops were consumed locally until demand is met (this is consistent with assumptions made by Baker et al. [2001] for their nitrogen [N] budget of Phoenix). We used the same net flux method for feed production; however, we know that the majority of feed, primarily alfalfa, is in fact produced locally (United

Dairymen Association, *personal communication*). Cotton is the only crop that is a net export, as processing does not happen locally. Cotton lint only contains trace amounts of P, but P exports in cottonseed for oil production are substantial for the agricultural sector (Unruh and Silvertooth 1996). We assumed annual steady state for agricultural vegetation and constant standing pools for orchards over the one-year study period (see Appendix A for more details).

Animals.—

1. *Pets.*—We considered cats and dogs only, as these are the predominant pets in Phoenix. Pet food is imported from outside of the greater Phoenix area, and we assumed that the majority of excreta goes to urban soils. We did not include estimates for wild animals because these fluxes are likely to be quite small. We obtained data on cat and dog populations from Baker et al. (2001) and L. Baker (*personal communication*), and nutritional needs and waste production of dogs and cats from the literature (Baker et al. 2007; Association of American Feed Control Officials, information *available online*).⁸ We used a P content value of 1% of body mass to estimate pools of P in cats and dogs, which is the same as humans because no specific information on other mammals was available (Harper et al. 1977).

2. *Livestock.*—The major livestock in the greater Phoenix area is the dairy cow. Approximately 40% of the milk produced in the Phoenix area is consumed locally and the remainder is exported (United Dairymen of Arizona [UDA], *personal communication*). Livestock feed consists of alfalfa and grains that are produced within the ecosystem. We assumed 100% of the manure excreted by dairy cows is applied to agricultural soils (Ruddy et al. 2006). Data on the local dairy-cow population were from the Census of Agriculture, and data on nutritional requirements and waste production for cows were from Hall et al. (2009) and the American Society of Agricultural Engineers (data *available online*).⁹ We estimated the pool of P in dairy cows using average P content value of 1% of body mass (Harper et al. 1977). We did not consider fluxes of P through other livestock, including poultry, cattle, calves, horses, and ponies, since these fluxes are negligible for the greater Phoenix area ecosystem (USDA 2007).

3. *Humans.*—Food for human consumption is both locally produced and imported into the Phoenix system. We calculated P consumption using U.S. per capita P consumption rates (NASS 2003) and 2000 population data from census blocks within our study boundary (CAP LTER, see footnote 12). Food waste along the food-supply chain from groceries to households is ~50%; therefore, we assumed that total demand for food P was double the amount of food consumed (Lundqvist et al.

⁸ <http://www.aafco.org/>

⁹ <http://www.mawaterquality.agecon.vt.edu/manuretable.php>

2008). We assumed that all vegetables, fruits, and grains that were produced within the greater Phoenix area and not used for livestock feed were consumed locally and subtracted this supply from demand to estimate imports of food to the ecosystem. Food P that is not consumed eventually ends up in landfills and wastewater (via garbage disposals; MAG 2005). Ninety-eight percent of P from food that is consumed eventually makes its way to wastewater and septic systems (Drangert 1998). We calculated the flux of P to soil via septic systems as the difference between the total wastewater production (per capita estimate from Baker et al. 2001) and the total capacity of wastewater treatment plants in Maricopa County (Maricopa Association of Governments, information *available online*).¹⁰ We estimated the pool of P in humans using average P content (Harper et al. 1977) and the population in the greater Phoenix study-area boundary in 2000 (CAP LTER, see footnote 12). We also calculated net immigration to the greater Phoenix area assuming annual increases were represented by a linear increase in population between 2000 and 2010 (U.S. Census Bureau 2010, see footnote 5; see Appendix A for more details).

Material environment.—Humans import products high in P such as cardboard, paper, wood, and textiles that accumulate in the city and landfills or leave the greater Phoenix area for recycling (World Resources Institute, data *available online*).¹¹ We obtained estimated fluxes of these materials to landfills and recycling plants from municipal trash analyses (MAG 2005). We obtained P concentrations from the literature (paper and wood, Antikainen et al. 2004; textiles, Yang and Yang 2005). Humans also use materials in building and road construction that have relatively high P concentrations, such as concrete and wood. We did not calculate the pools and fluxes of P in all of these materials due to the lack of available data. To calculate the pool of asphalt, we used remotely sensed data on land cover from Buyantuyev (*available online*)¹² to estimate the area of asphalt and assumed an average depth of 10 cm (Golden et al. 2009). We then used the P content for asphalt from the literature to estimate pools (see Appendix A for more details).

Analysis of the P budget

To better understand P dynamics in our system using the calculated P fluxes and pools at the ecosystem scale, we calculated the throughput and accumulation for each subsystem and accumulation for the entire ecosystem. Throughput is a measure of subsystem activity, measured here as the cumulative flux of P into and out of a subsystem. The throughput of an individual subsystem describes what is driving the demand for inputs, producing outputs, or both. As such, throughput can

be used to identify important management priorities both over space and by sector. Accumulation of P occurs when inputs to a system or subsystem exceed the outputs. At the scale of subsystems, sites of P accumulation (sinks) may represent P hotspots in the city landscape. Hotspots are potentially vulnerable to eutrophication, but may also present areas of opportunity for sustainable P management, by exploiting their high P concentrations to use as an input to P-poor subsystems. We also calculated turnover time for urban, agricultural, and desert land uses. We used soil, vegetation, and animal subsystems to calculate turnover because we had equivalent inputs and stocks for these subsystems only. Turnover time normalizes fluxes (in this case, inputs) by pools and gives an estimate of the average time that it takes to replace all of the P in the pool. We calculated throughput, accumulation, and turnover time according to the following equations:

$$\text{Throughput (Gg/yr)} = \frac{\text{all inputs to the subsystem (Gg/yr)} + \text{all outputs from the subsystem (Gg/yr)}}{(3)}$$

$$\begin{aligned} \text{Accumulation (Gg/yr)} = \\ \text{all inputs to the system or subsystem (Gg/yr)} \\ - \text{all outputs from the system or subsystem (Gg/yr)} \end{aligned} \quad (4)$$

$$\begin{aligned} \text{Turnover time (yr)} = \\ \frac{\text{all inputs to the system (Gg/yr)}}{\text{total pool in system (Gg)}}. \end{aligned} \quad (5)$$

Additionally, we calculated two separate aggregations for subsystem inputs and outputs. Subsystem inputs were calculated as the sum of all inputs into a subsystem (total inputs) and as the sum of all inputs that originated outside of the Phoenix study boundary. Total outputs from each subsystem were also calculated as the sum of all outputs from a subsystem. Outputs were also calculated as the sum of outputs from a subsystem that left the greater Phoenix ecosystem.

Spatially corrected P budget

We visualized and explored the areal distribution of P pools, inputs, and outputs across the urban ecosystem using the spatial budget. We matched the pools and fluxes of the P budget with existing spatially explicit data including census tract, land-cover class, land-use class, or in some cases, the intersection of a certain land cover and land use, which we refer to as land classes (see Appendix B for which P pools and fluxes were matched to which land classes). We obtained land classes from several data sets, including: 2000 census tract data (CAP LTER, *available online*),¹³ 2005 CAP land-cover data

¹⁰ <http://www.azmag.gov/Documents/pdf/cms.resource/208FinalReport.pdf>

¹¹ <http://earthtrends.wri.org/>

¹² <http://caplter.asu.edu/data/>

¹³ http://caplter.asu.edu/data/?path=/exist/rest/db/datasets/util/xquery/getDatasetById.xql?_xsl=/db/datasets/util/xslt/datasetHTML.xsl&id=knb-lter-cap.212.1

TABLE 1. Characteristics of subsystems in the greater Phoenix metropolitan area, Arizona, USA.

Subsystem	Total input (Gg/yr)	External input (Gg/yr)	Throughput (Gg)	Accumulation (Gg)	Total output (Gg/yr)	External output† (Gg/yr)
Soil	6.8	2.1	10.2	3.5	3.3	0
Water	2.8	0.1	4.9	0.8	2.0	0.2
Vegetation	4.7	0.0	7.9	1.4	3.3	0.9
Animal	2.4	0.1	4.5	0.4	2.1	0.1
Human	4.1	4.0	8.1	0.2	4.0	1.7
Material environment‡	0.2	0.2	2.7	-2.4	2.4	2.4
Landfills	4.6	0.0	4.6	4.6	0	0

† Considers waste to landfill as an external output.

‡ Negative accumulation is due to lack of data on inputs to the system.

(Buyantuyev 2007; see footnote 13), agricultural data from USDA (NASS 2010), 2000 land-use data (Redman et al. 2005), and dairy farm data (Goggle Earth 2011). Some landfills serving the greater Phoenix area are located outside (though near) the study area boundaries, and thus landfills were not represented on the spatial distribution of P, although they are considered part of greater Phoenix area P system.

Other than for landfills, we used the latest available data that encompassed all of the Phoenix study area. We resampled each land-class data set to a 90-m² pixel resolution to maintain similarity among data sets. We used ArcGIS (ESRI 2009) to create land classes that required the intersection of two or more data sets. For all pools, inputs, and outputs, we uniformly applied the total P value across the relevant pixels. Thus, the spatial representation of pools, inputs, and outputs were calculated by dividing the total P value associated with the land class by the number of 90-m² pixels encompassed by the land class.

Uncertainty

Quantification of uncertainty is a concern for ecosystem mass balance studies. We used a combination of literature data and site-specific data to create our budget estimates. Our calculations, data sources, and assumptions have been made explicit within the paper and are available in detail through Appendices A and B. We placed special emphasis in this paper on the transparency of our data sources, assumptions, and the limitations of our calculations. Such transparency will permit replication and a discussion of how our results can be used for nutrient-management applications.

TABLE 2. Annual fluxes of P through the soil subsystem.

Component	P flux (Gg/yr)
Chemical fertilizer to agricultural soils	1.60
Effluent to soils	1.83
Biosolids to agricultural soils	1.67
Manure to agricultural soils	1.04
Pet waste to soils	0.72
Chemical fertilizer to residential soils	0.30
Atmosphere to soils	0.27
Yard trimmings to soils (compost)	0.20
Groundwater to soils	0.03
Runoff	-0.44

RESULTS

Fluxes

The greater Phoenix metropolitan area is a net P sink (inputs > outputs). The largest P input to the greater Phoenix area is food for human consumption, representing 48% of inputs, followed by fertilizer to agricultural soils, representing 24% of inputs (Fig. 2, Tables 1–3). Total P outputs from the ecosystem are more than an order of magnitude smaller than total inputs to the ecosystem. P outputs from the greater Phoenix area collectively represent just 0.7% of total inputs (Fig. 2, and see Tables 4–6 for values). Many of the largest fluxes are completely internal to the ecosystem and represent recycling of P within the greater Phoenix area. The largest internal fluxes include human waste to wastewater treatment facilities (Table 3), feed crops to cows (Table 7), the application of manure from local livestock to agricultural soils (Table 5), and the recycling of wastewater and biosolids for agricultural irrigation and fertilization (Table 2).

Water is an important vector for P transport in most systems (Bennett et al. 2001). In the greater Phoenix system, runoff from urban land cover represents a small flux of P from soils and the built environment to surface water (Table 4). In reality, this flux may be even lower than our estimate due to retentive stormwater infrastructure designed to reduce runoff from reaching surface waters. Runoff from desert land cover was negligible: an order of magnitude lower than fluxes from the urban area. Although fluxes from wastewater treatment plants to surface water are quite high (0.6 Gg P/yr), fluxes of P in the Gila River ~60 km downstream of the 91st Avenue sewage treatment plant

TABLE 3. Annual fluxes of P through the human subsystem.

Component	P flux (Gg/yr)
Food imports	3.83
Local dairy production	0.14
Local food production	0.11
Net human immigration	0.1
Human food to wastewater	-0.32
Human food to landfill	-1.69
Human excreta to wastewater	-1.95

TABLE 4. Annual fluxes of P through the water subsystem.

Component	P flux (Gg/yr)
Sewage discharge to water treatment plants	2.74
Surface water inputs†	0.56
Surface water to urban system (residential and industrial uses)	0.04
Wastewater to surface water (runoff)	0.04
Surface water to soil (irrigation)	0.02
Groundwater withdrawals to:	
Soil (irrigation)	0.03
Urban system	0.01
Groundwater recharge from:	
Surface water	−0.02
Wastewater	−0.09
Surface water outputs	−0.11
Wastewater to soil (biosolids)	−1.67
Wastewater to soil (effluent irrigation and septic)	−1.83

† Includes the Gila, Salt, and Verde Rivers, and the Central Arizona–Phoenix (CAP) canal.

are considerably lower (0.11 Gg P/yr), indicating that this river may be a significant sink for P.

Pools

Soils dominate P pools, representing 55% of total pools, followed by asphalt, vegetation, and humans (Table 8). Desert soils account for the most total soil P storage due to their large area; however, on a per area basis, P storage is greatest in agricultural soils, followed by desert and urban soils (Table 8).

Human population density shapes the concentration of P pools, directly through P storage in humans themselves, as well as through human's influence on their immediate environment (Table 9). That is, urban areas with a high density of people also concentrate pets, landscapes with high-P vegetation and soils, and material and built-environment components like asphalt (e.g., the street grid pattern is visible in Fig. 3). Additionally, the agricultural P pool is an important, if not a dominant, feature of P storage (see Fig. 1 for land-use distribution).

Accumulation, throughput, and turnover

All subsystems were net sinks for P (outputs = 0.4900 × inputs; $R^2 = 0.18453$). However, it is important to note that we did not include the material environment subsystem in the accumulation representation of Fig. 4

TABLE 5. Annual fluxes of P through the animal subsystem.

Component	P flux (Gg/yr)
Local feed to cows	1.74
Food imports to pets	0.7
Dairy production to human food supply	−0.14
Dairy production for export	−0.14
Pet waste to soils	−0.72
Livestock manure to soils	−1.04

TABLE 6. Annual fluxes of P through the material environment subsystem.

Component	P flux (Gg/yr)
Paper and cardboard import	0.30
Paper and cardboard to recycling	−0.06
Textiles to landfills†	−0.10
Other waste to wastewater	−0.45
Paper and cardboard to landfill‡	−1.13

† No data about textile imports are available.

‡ No equivalent import data.

as we have incomplete data that prohibits an accurate depiction of the subsystem dynamics. We predict that the material environment would likely be a strong sink for P as physical infrastructure, like roads and households, which accumulate materials not disposed of in landfills or through recycling, expand over time. Landfills and fluxes related to waste were not represented on the P accumulation map (Fig. 5) specifically because landfills are physically located outside of (but near to) our study system boundary. Nevertheless, landfills represent a major sink for P in this ecosystem and are represented in other accumulation representations. Excluding landfills, most accumulation occurred in agricultural soils (1.73 Gg P/yr; Fig. 5 and Table 1), whereas groundwater was a small sink, accumulating 0.07 Gg P/yr. The greater Phoenix area accumulated 6.02 Gg of P in 2005, when including landfills and all other subsystems (9.4 kg/ha; see Table 9 for land use-specific P accumulation).

At the subsystem level, total soils had the largest throughput, followed by humans and vegetation (Table 1). This pattern is driven by large imports of fertilizer to agricultural and urban soils and food for human consumption. Vegetation throughput is high as a result of agricultural uptake and harvest (Table 1). When soils are disaggregated by land use, however, humans have the highest throughput (Fig. 4). This pattern of throughput is clearly visible on the landscape, where throughput was high in areas with high human densities, agricultural production, and dairy production (Fig. 6). The domination of P fluxes by agriculture and humans (through the production and consumption of food and the production of waste) demonstrates the importance

TABLE 7. Annual fluxes of P through the vegetation subsystem.

Component	P flux (Gg/yr)
Agricultural crops (plant uptake)	3.36
Mesic vegetation (plant uptake)	0.99
Desert vegetation (plant uptake)	0.19
Xeric residential vegetation (plant uptake)	0.1
Nonresidential vegetation (plant uptake)	0.02
Cotton exports	−0.001
Crops to human food supply	−0.11
Desert vegetation (litterfall)	−0.19
Yard trimmings to soils	−0.2
Yard trimmings to landfill	−0.87
Field crops to animal feed	−1.74

TABLE 8. Phosphorus pools in the greater Phoenix ecosystem.

Known pools (2005)	Total P (Gg)	Area (km ²)	Storage per area (kg P/ha)
Desert soil	8.5	2785	30.5
Asphalt	7.3	298	234.1
Agriculture soil	4.2	697	60.2
Desert vegetation	4.2	713	58.8
Xeric residential soil	3.9	772	50.5
Humans	3.2	...	...
Xeric residential vegetation	2.0	772	25.9
Cows	1.9	68	279.1
Mesic residential soil	0.8	380	21.0
Mesic residential vegetation	0.5	380	13.1
Urban nonresidential soil	0.4	768	5.2
Urban nonresidential vegetation	0.2	768	2.6
Pets (cat and dogs)	0.1	...	...
Agriculture vegetation (tree crops)	0.1	7	139.7

Note: Ellipses indicate that no data are available.

of the food system to urban P dynamics. Both spatial (Figs. 5 and 6) and subsystem approaches (Figs. 2 and 4) attest to the importance of food-related P fluxes both in driving imports and exports of P, but also in recycling fluxes.

While throughput is a valuable metric for understanding the importance of subsystems in driving system dynamics, it is strongly affected by the size of the subsystem. Turnover time (pool/inputs, in units of time) gives an estimate of the average time for all P in a pool to be replaced and thus is an index of how quickly P is cycled. We calculated turnover time for desert, urban, and agricultural land uses and found that human activity strongly speeds turnover time (Table 9).

DISCUSSION

The budget and landscape of the greater Phoenix metropolitan area

The greater Phoenix metropolitan ecosystem is a net P sink. Humans control the movement of P via import and production of food, recycling of water, and management of solid waste. Compared to the desert subsystem, urban and agricultural land uses were characterized by larger fluxes (total and per area), high rates of accumulation, and rapid turnover of P pools. Despite the predominance of human control, the biophysical characteristics of the ecosystem, including soil chemistry, low rainfall, and limited number of freshwater bodies (e.g., lakes and rivers) also play a major role in how and where P accumulates. Taken as a whole, the distribution of throughput and accumulation values of subsystems in the greater Phoenix ecosystem is unique and supports the concept of a distinct urban biogeochemistry developed in Kaye et al. (2006).

Comparison to other urban systems

Urban P budgets are context specific, and a comparison of known urban P budgets illustrates the variability of urban biogeochemical cycling. The rates of nutrient

retention and the magnitude of fluxes to and from urban areas vary across cities, although all retain P. Phoenix accumulates 86% of P inputs, while Bangkok, Thailand, accumulates 59% (Faerge et al. 2001) and Gälve, Sweden, accumulates 67% (Nilsson 1995). Mesic cities with closer proximity to water, such as Gälve and Bangkok, retain less P than Phoenix (Nilsson 1995, Faerge et al. 2001), supporting our findings that P recycling in Phoenix is largely driven by water recycling due to water scarcity. Less-developed cities with smaller populations, such as Harare, Zimbabwe, consume less P and have much smaller P outputs from their sewage infrastructure than Phoenix (Gumbo et al. 2002). Our Phoenix P budget is more comprehensive than many other urban budgets because it includes aspects of the built environment that other budgets have not included. This makes full cross-city comparisons difficult. A recent study by Han et al. (2011), which included a spatial analysis of net anthropogenic P accumulation in the Beijing metropolitan region, supported our conclusion that human population density and local agricultural production with chemical fertilizers are important predictors of P movement in the urban environment. In general, differences among urban systems appear to be influenced by the biophysical characteristics of the environment (especially rainfall, proximity to water, and soil characteristics), level of economic development (as it affects land use, fertilizer use, and waste management technology), wealth (as it affects diet), and human population size.

Current state of Phoenix: the role of agriculture and water

The greater Phoenix P budget, including the spatial distribution of fluxes and pools, was dominated by agricultural and food-related fluxes (Figs. 5 and 6). Eighty percent of imports were related to the food system, and most internal fluxes were transfers along food production–consumption chains. Large food-related fluxes contributed to rapid turnover times for both agricultural and urban subsystems. Large internal fluxes, including the application of manure, biosolids, and wastewater on agricultural lands, represented recycling among human, livestock, water, and soil subsystems, leading to system P dynamics that appeared more cyclical than linear (Fig. 2).

A large portion of reuse was related to water management. Modification of local hydrology occurs

TABLE 9. Characteristics of land uses in the greater Phoenix metropolitan area.

Land use	Turnover time (yr)	Input (kg P/ha)	Output (kg P/ha)	Accumulation (kg P/ha)
Desert	36.0	1.3	0.7	0.6
Agriculture	0.9	100.8	48.0	28.5
Urban	1.8	31.4	30.3	1.1

Note: Numbers only consider soils, vegetation, and animals for each land use, assuming equal distribution of pools and fluxes.

FIG. 3. Spatial distribution of pools across the Phoenix ecosystem. Phosphorus is concentrated in densely populated areas where patterns of streets are visible because of P in asphalt. Pools included are vegetation, soils, asphalt, dairy cows, humans, and pets. The image was smoothed using focal statistics with a five-cell radial filter.

in response to concerns about water scarcity, yet plays a major role in internal P cycling, such as when wastewater effluent is applied to agricultural fields. Lauver and Baker (2000) showed that the regional focus

on water availability and subsequent water management decisions shaped the Phoenix N cycle in similar ways. Therefore, current P recycling is an unintended consequence of the management of another resource. Apart

FIG. 4. Urban ecosystem phosphorus activity: inputs and outputs of P to and from subsystems. Circle color indicates subsystem domain (animals, landfills, soils, vegetation, and water), and circles size indicates throughput (input + output). The dashed line is a 1:1 line representing an equal amount of inputs and outputs. Subsystems below the dashed line accumulate P, while subsystems above are sources of P. The material environment is not included because of incomplete data.

from deliberate water recycling, local hydrology also plays an important role in limiting the risk of eutrophication associated with P in agricultural soils and in cities. Phoenix and the surrounding Sonoran Desert have low rates of precipitation and high rates of evaporation, so most runoff evaporates before reaching surface-water bodies (i.e., the Salt River). Stormwater engineering, such as retention basins, further limits downstream fluxes. Therefore, both deliberate management of water resources and the nature of local hydrology shape P cycling. Management of the urban P cycle should include input from water managers who would explicitly consider the link between water and P cycling in best management strategies for the future, especially to minimize trade-offs and maximize synergies between water and nutrient management.

*Current state of Phoenix:
the material and built environment*

Although fluxes were dominated by agricultural production and animal food consumption, storage of P in the greater Phoenix area was concentrated in dense human populations and their associated built environment (Fig. 3). These pools have accumulated over years of urbanization and population growth. Even though we were not able to calculate them in this article, fluxes of construction materials such as concrete are undoubtedly substantial in this ecosystem, especially during periods of rapid growth. As a crude estimate of accumulation, we multiplied the amount of P stored in asphalt per area of urban land use by the increase in urban area from 1975 to 2005. Accumulation of P due to asphalt alone amounts to 0.15 Gg/yr (4.42 Gg P over the past 30 years); including all other construction materials would increase this number substantially. Gross fluxes are probably considerably higher given patterns of construction and demolition. Finally, landfills store a substantial amount of P and are the largest sink for P within this ecosystem.

One of the most important limitations in our assessment of the material and built environment (as well as with other subsystems) was limited practitioner participation. For varieties of reasons (limited resources or constraints on information), government agencies do not always collect or make available the necessary data for researchers to compile a complete nutrient budget. As discussed in the next sections, it will be necessary to create partnerships with practitioners not only to collect better data, but also to better manage P cycling for more efficient use and recycling.

Efficiency and other metrics of P management

Sustainable P management should address both problems related to the limited supply of mineral P as well as problems of pollution downstream of urban and agricultural areas. The challenge is to minimize inputs and losses as pollution while still maintaining productive output, such as agricultural production and human well-

being. Traditional metrics for urban nutrient budgets, such as retention, only consider the reduction of losses downstream. We argue that *efficiency*, defined as the non-waste output of a system per unit of P input, is a more useful metric for holistic P management. Increasing efficiency of the whole greater Phoenix ecosystem would require minimizing external inputs and wastewater outputs and thus requires more internal recycling. Spatial efficiency within Phoenix will also be important as to ensure the P is not concentrating in areas where it is detrimental to the ecosystem, or P is useful. However, the involvement and “buy-in” of practitioners is critical to efficiency, recycling, and reuse.

Central to the collaboration of practitioners, scientists, and policy makers is the underlying need for them to be aware and concerned with P cycling. Thus, the first step in collaboration is finding common goals related to P management. Although Phoenix has limited risk for downstream eutrophication due to local arid system hydrology, Phoenix is a major center for P consumption that contributes to and is vulnerable to global P scarcity (as described by Cordell et al. 2009). P security should be an important issue for Phoenix managers and citizens for two reasons, one global and one local. Consumption of P in Phoenix is linked to the global P cycle, a cycle in which an unequally distributed nonrenewable resource must serve an increasing number of people, and where both biophysical and human realities have resulted in food insecurity (most notably in Africa; Sanchez 2002). Regardless of local issues, sustainable P management in Phoenix, and other cities worldwide, is important for the future sustainable availability of P globally. However, global scale P scarcity has local consequences, primarily via a significant effect on the price of fertilizer, and therefore food (Cordell et al. 2009).

Dependence on mined P increases the vulnerability of citizens, especially urban ones, who do not produce their own food, to global fluctuations in the price of P, and thus, the price of food. Phoenix is no exception and the management strategies that affect P efficiency and recycling in Phoenix directly affect: (1) agricultural and food-industry stakeholders for whom P is an essential input for production, (2) residents who are dependent on the agro-industrial complex to produce their food (as price fluctuations related to P would directly affect food prices), and (3) government, waste, and water management agencies as governing bodies that respond to the need of residents. Opportunities for increased efficiency and recycling in greater Phoenix lie predominately in the human, vegetation, and material environment subsystems that currently produce large amounts of solid waste that accumulates in landfills or is exported to other cities (Table 1). There are multiple strategies to increase and alter efficient P management through recycling. Some lie in altering the food system, while others may concern nonfood items high in P such as detergent or P used in steel production (Decker et al. 2000, Matsubae-Yokoyama et al. 2009). The existing land-use heterogeneity in

FIG. 5. Spatial distribution of accumulation of P in the greater Phoenix metropolitan ecosystem. High accumulation (input – output) occurs in agricultural areas. Note that this accumulation is for each 90-m² cell (equal to 90-m pixel). Fluxes included in the map are atmospheric deposition, humans, pets, food, agricultural products, organic waste, and fertilizer.

FIG. 6. Spatial distribution of throughput in the greater Phoenix metropolitan ecosystem. High throughput (input + output) occurs in agricultural and urban areas. Note that this throughput is for each cell. Fluxes included in the map are atmospheric deposition, humans, pets, food, agricultural products, organic waste, and fertilizer.

PLATE 1. View of Phoenix metropolitan area (Arizona, USA) showing the extent of human settlement in this desert landscape. Photo credit: Edgar Cardenas.

greater Phoenix, i.e., land uses that concentrate P (e.g., households) are in proximity to land uses that require P inputs (agriculture), could be better utilized to recycle waste. Taking advantage of such proximities by using small-scale and decentralized strategies would minimize transportation costs and thus lower the cost of recycling, and therefore may be better than centralized recycling.

Future scenarios

While we have provided a snapshot in time to understand P cycling in the Phoenix ecosystem, it is critical for managers to consider possible future scenarios. We introduce a scenario for Phoenix based on two important drivers of P cycling: population growth and agricultural declines as agricultural lands are converted to residential neighborhoods. We qualitatively explore the implications of these two dominant trends for P cycling and management, noting especially how these changes cascade through the P cycle. These scenarios are not intended to be predictive, but to illustrate the importance of a holistic understanding of urban P cycling both spatially and temporally and the need for more extensive scenario analysis.

Phoenix is one of the most rapidly growing cities in the United States. This net growth is expected to continue (Gammage et al. 2011), which will likely result in a rise in food imports and wastewater generation, as well as other fluxes associated with humans (e.g., fluxes of pet food and waste, building materials, and trash). The net effect of increasing human population would therefore be to increase throughput for most subsystems.

As agricultural land use declines due to conversion to urban and residential land uses, fertilizer inputs to the system will decline, as will crop and dairy exports from the region. Some of the biggest changes, however, will likely come from cascading effects. Decreased crop production will necessitate increased food imports for human consumption. Decreased agricultural land will mean less irrigation water and a smaller flux of P from surface water to soils. Finally, and perhaps most importantly, this will result in a decrease in the recycling of wastewater treatment plant effluent. With reductions in effluent reuse, and the P it carries, wastewater will have to go elsewhere: recharged to groundwater or returned to surface water.

In the future we expect a major switch in the way the P cycles through the system. Phosphorus cycling in the greater Phoenix area is characterized by a remarkable amount of recycling from human waste to agricultural fields. Due to a growing source of P (humans) and a shrinking sink (agricultural soils), we expect that wastewater effluent distribution will undergo drastic changes. This can take the form of a large export of P from the great Phoenix area or altering internal cycling to other subsystems. This highlights two important points. First, the combinatory effect of status quo land-use and population changes will greatly impact the future P cycling regime. Second, the circumstances that lead a city to be a strong sink or source of nutrients are strongly contingent on land-use patterns and other socioeconomic drivers and are likely to change substantially over time (and are place specific).

The deliberate and sustainable management of P resources through waste (especially food and yard waste) and water management is paramount to a sustainable (and a desirable) future urban state for residents and industry (especially agricultural). Ultimately, the development of any future scenario is in the hands of Phoenix residents and resource managers, and thus, they should be involved in the co-production of the knowledge about the current state of P and what they would like their city to look like in the future (Clark et al. 2006).

The explicit involvement of practitioners who directly affect P cycling (e.g., wastewater treatment plant officials, construction companies, city offices) in research would facilitate the creation and implementation of more effective P management plans because: (1) practitioners could increase our understanding of current P cycling with their knowledge of the system (including data), (2) outcomes may be more compatible with managers needs and these managers may better understand results, and (3) this involvement would facilitate a transition towards P sustainability. Cordell and colleagues (2011) suggest a useful framework for guiding decision-making toward sustainable P recovery and reuse. This framework is a good guide for researchers and practitioners to evaluate and collaborate on the suggestions we put forth here.

Considerations for future work

We have emphasized the need for future work in urban nutrient budgets to involve practitioners in order to move toward a future with greater P efficiency, reuse, and recycling. Cordell et al. (2011) give examples where recovery and reuse strategies have been successful and help both researcher and practitioners imagine what may be possible elsewhere (bearing in mind the importance of local cultural and biophysical factors). In addition, we believe it is important to include a spatial perspective in future work, and explicitly study P cycling in relation to other resources (e.g., nitrogen, energy, water, et cetera).

We used a spatially corrected approach, which we believe increases the relevance of our results to practitioners (GIS files of these maps are publically available online).¹⁴ The visualization of P pools and fluxes increases understanding about the concentration and dispersion of P in the environment. Since pools and fluxes within an urban ecosystem are dominated by humans and their institutions, the development of maps will be important for management decisions because of the rapid change in land covers over small areas. Urban environments are dominated by complex morphology as a result of spatial competition and multiple institutions driven by economics (Batty 2008). Maps of P distribution are critical and should be combined with other social and ecological spatial data to determine appro-

priate management decisions that consider the complexity of urban form and social processes, especially how we can use the spatial heterogeneity of the city to minimize transportation costs (especially where transportation costs are viewed as a disincentive for recycling). Such maps could also be used to track the effect of management practices and thus serve as an indicator of success toward more efficient and cyclical P management. Future work should continue to explore P sustainability spatially.

In addition to increasing knowledge about current cycling of P, and developing desirable future scenarios and management strategies, future work must consider P cycling from a systems perspective. Nutrients do not cycle in isolation; it is insufficient to manage for a single nutrient (Sterner and Elser 2002, Conley et al. 2009). In order to holistically understand and truly manage urban P efficiently, we must examine its relationship with multiple resources (e.g., N, C, energy, and water). Such analyses will aid decision makers to better understand the synergies and trade-offs of management options and facilitate the creation of sustainable nutrient management plans. For example, current water-recycling strategies have been synergetic with P recycling, but other P management strategies to increase recycling like urban agriculture may have trade-offs because of heavy metal contamination in soils and effluent sludge (McBride et al. 1997). The necessity to consider multiple resources continues to emphasize the need for collaboration between multiple parties to effectively study and manage complex urban ecosystems as cities become dominant features on the landscape.

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SUPPLEMENTAL MATERIAL

Appendix A

Calculations, assumptions, and values used to determine stocks and fluxes of phosphorus in Phoenix, Arizona, USA (*Ecological Archives* A022-040-A1).

Appendix B

Calculations, assumptions, and data sources used to spatially represent the phosphorus budget of Phoenix, Arizona, USA (*Ecological Archives* A022-040-A2).