Phosphorus Cycling in Metropolitan Phoenix

by

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ABSTRACT

Phosphorus (P), an essential element for life, is becoming increasingly scarce, and its global management presents a serious challenge. As urban environments dominate the landscape, we need to elucidate how P cycles in urban ecosystems to better understand how cities contribute to—and provide opportunities to solve—problems of P management. The goal of my research was to increase our understanding of urban P cycling in the context of urban resource management through analysis of existing ecological and socio-economic data supplemented with expert interviews in order to facilitate a transition to sustainable P management. Study objectives were to: I) Quantify and map P stocks and flows in the Phoenix metropolitan area and analyze the drivers of spatial distribution and dynamics of P flows; II) examine changes in P-flow dynamics at the urban agricultural interface (UAI), and the drivers of those changes, between 1978 and 2008; III) compare the UAI's average annual P budget to the global agricultural P budget; and IV) explore opportunities for more sustainable P management in Phoenix. Results showed that Phoenix is a sink for P, and that agriculture played a primary role in the dynamics of P cycling. Internal P dynamics at the UAI shifted over the 30-year study period, with alfalfa replacing cotton as the main locus of agricultural P cycling. Results also suggest that the extent of P recycling in Phoenix is proportionally larger than comparable estimates available at the global scale due to the biophysical characteristics of the region and the proximity of various land uses. Uncertainty remains about the effectiveness of current recycling strategies and about best management strategies

for the future because we do not have sufficient data to use as basis for evaluation and decision-making. By working in collaboration with practitioners, researchers can overcome some of these data limitations to develop a deeper understanding of the complexities of P dynamics and the range of options available to sustainably manage P. There is also a need to better connect P management with that of other resources, notably water and other nutrients, in order to sustainably manage cities.

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Chapter 1

INTRODUCTION

Motivations

Many scientists have recognized that our traditional disciplinary and linear way of looking at the world and of solving problems is no longer adequate for either understanding or deriving solutions to complex problems (Funtowicz & Ravetz, 1993). Policy-makers have also recognized that the challenges of a rapidly changing world, where uncertainty is fundamental, require a new way of solving problems. Sustainability (which I consider here to include sustainability science and sustainable development) is one way to understand and attempt to solve complex problems. According to Agyeman, Bullard, & Evans (2003) sustainability considers "the need to ensure a better quality of life for all, now and into the future, in a just and equitable manner, whilst living within the limits of supporting ecosystems" (pg.5). Sustainable development requires us to protect long-term life support systems so that people now and in the future can equitably meet their needs and preserve their freedom to choose how they live. To participate in sustainable development, we need to accept uncertainty, avoid actions that lead to irreversible consequences, limit resource depletion and waste production, and take collective responsibility. We must embrace these principles across all sectors of society, for the problems we face and for finding solutions to them.

Sustainability researchers strive to understand social and environmental interactions, particularly the key feedbacks in socio-ecological systems (Kates, et al., 2001; Sarewitz, et al. 2010). Only by understanding these feedback dynamics can we intervene to mitigate their harmful effects and conserve or enhance beneficial effects. Sustainability scientists also aim to participate in decision-making processes as opposed to simply providing information to decision-makers. Gibson (2006) proposed eight criteria to assess the sustainability of a system: 1) socio-ecological system integrity; 2) livelihood sufficiency and opportunity; 3) intragenerational equity; 4) intergenerational equity; 5) resource maintenance and efficiency; 6) socio-ecological civility and democratic governance; 7) precaution and adaptation, and; 8) immediate and long-term integration. We can use these assessment criteria to identify the kinds of problems that sustainability research and practice are best suited to tackle. Problems that fit these criteria are complex, urgent, exhibit long-term dynamics, involve cross-sectoral and cross-scalar interactions, and whose solutions are specific to a place and time. Sustainability researchers call these "wicked problems." Wicked problems cannot be fully understood because they are complex, are understood differently by different people, are constantly changing, imply solutions that are neither right nor wrong, and are novel and unique (Conklin, 2006). Every attempt to address a wicked problem has consequences, and as we change management strategies to "solve" a problem, the nature of the problem changes. Instead of increasing knowledge to control uncertainty in management strategies, sustainability scientists allow for uncertainty in both the way they understand problems and the way they propose solutions to them.

Framing the problem of P management

One wicked problem that has become apparent recently is phosphorus (P) management. Phosphorus is a scarce resource, and has reemerged as a concern in 2008 (it was also recognized as a concern in the 1930'a by President Roosevelt), when it became an issue of interest in both scientific and social arenas (United Nations Environmental Programme, 2011). Phosphorus is an essential mineral for plant growth, and high crop yields since the Green Revolution have relied on an inexpensive supply of mined phosphate, which is a non-renewable resource. Phosphorus demand has increased almost twenty fold since 1800 (Cordell, Drangert, & White, 2009). Because only three countries control 93% of the currently known reserves of economically minable P (Morocco, China, United States; Jasinski, 2011; Van Kauwenbergh, 2010), there have been concerns about the continued availability of cheap P, and concerns about price fluctuations in phosphate fertilizers and unequal burdens of these price fluctuations across the globe. Price fluctuations P resources have already played an important role in fluctuating food security. Just prior to the 2008 global food crisis, P fertilizer prices increased between 500 and 700% globally (Childers, Corman, Edwards, & Elser, 2011). In response to the increase, China imposed at 135% export tariff on P (Cordell, et al., 2009). Due to a market failure; current price structures prevent effective responses to P scarcity. Subsidization of P fertilizers, unequal distribution of P demand and P availability, the essential role of P in food security, and the economic externalization of P pollution effects on aquatic ecosystems together make our current management of P resources inadequate.

Unless we radically change how we manage P resources problems will only worsen.

Although there is still debate about whose needs, desires, and opportunities are considered in sustainable development, one can say that the provision of certain basic needs such as sufficient food and clean water to all, and the environmental stewardship necessary to satisfy these needs in the long-term are key to all six of Gibson's sustainability criteria. The management of key resources, such as P, to satisfy these needs, may be characterized as wicked problems of sustainability.

There are no substitutes for P because it is biologically essential. There are, however, substitutes for the way we use P. Once P is used (in crops and animals) it does not lose its utility. Unlike energy, which can only be transformed, P cycles. Thus instead of material substitution (as in the case of changing our energy source from fossil fuels to nuclear), there may be "process substitution" with P. That is, we may recycle P back into the production stream after it has been used. In ecosystems not dominated by humans, P is very tightly cycled (Chapin, Matson, & Mooney, 2002). If we were to replace the linear path of P through our food system with a more cyclical one, we would dramatically reduce the need for mineral P resources. Finding ways to change linear P resource use to more cyclical processes that are effective both globally and locally is a problem that requires a transdisciplinary solution.

Mineral P resources are controlled by only a few countries, making the current and future distribution of P very uncertain. China has already made political decisions (export tariffs) that affect the availability of P elsewhere. These types of decisions induce political tensions that will only increase as resources decline and demand increases. For example, P reserves in the US (Florida in particular, currently the largest supplier of P in the U.S., will most likely be depleted by 2030 (Cordell, Schmid-Neseta, Whiteb, & Drangerta, 2009). The extraction and processing of phosphate rock requires large amounts of sulfuric acid and petroleum-based energy (May & Sweeney, 1984). The production of both are also concentrated in a few regions of the world which adds to the complexity of possible economic scarcity.

The needs for P in food production are also unequally distributed across the globe. In sub-Saharan African and in most countries with tropical soils, P is the limiting nutrient for plant growth. Agricultural production requires increases in P fertilizer application to maintain high yields for increasing human populations (Drechsel, et al., 2004; Van Wambeke, Rom, & Land, 2004). On the other hand, in many parts of the United States and Europe, P has been over applied for many years, leading to high concentrations of P in runoff and consequent freshwater eutrophication (Bennett, Carpenter, & Caraco, 2001; Carpenter, et al., 1998). While the benefits of recycling on decreasing downstream pollution are most important to developed countries, the effect of recycling on the price and availability of P may be more important to developing countries. These different regions also have different availability of capital, labor, and technology to deal with P scarcity and eutrophication.

Although the vulnerability of societies to P scarcity and eutrophication varies across the globe, the connection between P resource management and food security is universal. Food security, which is a priority at all scales, is directly related to access to P resources. Thus, P resource security is a key component to national security, and household livelihood provisioning. Even in the face of spatial heterogeneity of P resources and P needs and thus concerns about P management, the future of mined-P resource extraction and the use of recycled P should be a shared concern for all countries, from the national to the household scale.

It is possible that additional P-rich deposits will be found and as technology improves, the time frame of peak extraction and eventual depletion may change. However, the long term outcomes, and the general path of P extraction will not change (Cordell et al., 2009). The long term equilibrium will still be the depletion of economically viable P stocks, like that of all non-renewable resources (Hotelling, 1991). We need to manage P in a more sustainable way that fosters inter- and intra-generational equity, and socio-ecological integrity. To do that, we need to reduce downstream pollution and reduce uncertainty about supply, thus closing the human P cycle.

Cities drive the need for P because they concentrate food consumption and they drive P eutrophication because high-P waste concentrates in and downstream of cities. Urban ecosystems are and will continue to be "hot-spots" for P activity. In this thesis, I concentrate on how P cycles in urban environments, and how large-scale agricultural production utilizes P at the interface with cities.

Study goals

Kates et al. (2001) and Sarewitz et al. (2010) emphasized the importance of understanding the interactions between social and ecological characteristics, and between global and local scales. In my study, I tried to increase our understanding of how human decisions and local ecological context shape P cycling in an arid city with a land use mosaic that incorporates large-scale agriculture. I also compared local and global P dynamics in order to highlight how solutions to sustainable P management differ by scale and location. This thesis:

1. Characterizes the stocks and flows within the Central Arizona-Phoenix Long-Term Ecological Research Site (CAP), which includes the Phoenix Metropolitan area.
2. Explores the drivers of change in the P dynamics of Phoenix's urban-agricultural interface.
3. Explores the role of biophysical and economic factors in shaping current P cycling in Phoenix, and at its urban-agricultural interface, and the opportunities for more sustainable P management.
4. Provides recommendations for future research and sustainable P management in Phoenix, especially at the city's urban-agricultural interface.

In Chapter Two, I explore P cycling in the Phoenix metropolitan area in order to better understand nutrient cycling in urban environments. A complete P budget shows managers where there are opportunities for, and barriers to, better P management. My research included: 1) calculating the magnitudes of major fluxes and stocks across the ecosystem boundary and among subsystems; 2) determining the spatial arrangement of P movement and storage in the urban ecosystem; and, 3) tracing major P fluxes and stocks to social, technological, and biophysical characteristics of the study system. I then synthesized this information to frame my findings in relation to sustainable urban P management.

The complete P budget of Phoenix showed that agriculture and food were the most important subsystems contributing to P imports, and to many of the recycling dynamics within the city. Therefore, in Chapter Three, I: 1) describe how the agricultural system in and around the Phoenix Metro area changed between 1978 and 2008, using Maricopa County as the study unit; and; 2) explore how drivers of P dynamics have changed over time. I also compare Maricopa County agricultural P cycling to global agricultural P cycling.

Chapter 2

PHOSPHORUS IN PHOENIX: A BUDGET AND SPATIAL EXPLORATION OF PHOSPHORUS IN AN 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 non-living 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; Childers et al., 2011; Cordell, et al., 2009), leading to eutrophication of aquatic systems (Bennett, et al., 2001; Smith & Schindler, 2009). The United Nations has recently highlighted that sustainable management of P resources is necessary to ensure global food security and minimize freshwater pollution (United Nations Environmental Programme, 2011). Changes in nutrient management will have to occur at all scales, from the local to the global, and strategies will need to be scaled and context specific.

Urban systems are focal to anthropogenic changes of biogeochemical cycles (Grimm, Faeth, Golubiewski, & Redman, 2008; Kaye, Groffman, Grimm, Baker, & Pouyat, 2006). 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 & Ramankutty, 2008), their ecological impacts extend far beyond the boundaries of urban settlement (Folke, Jansson, Larsson, & Costanza, 1997; Vitousek, Mooney, Lubchenco, & Melillo, 1997). 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, Jenerette, Wu, & Grimm, 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, Foppen, Uhlenbrook, Kulabako, & Muwanga). 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 chapter I construct a holistic urban P budget to contribute to the understanding of urban ecosystem function in a way that is compatible with city managers’ needs for decision-making.

Nutrients budgets are a useful accounting tool because they quantify inputs, internal fluxes, outputs, and stocks in order to understand nutrient movements. Previous urban nutrient budgets suggest that, while fluxes and stocks 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, Magid, & Penning de Vries, 2001). Previous urban P budgets have focused primarily on urban food systems (Riina Antikainen, Haapanen, Lemola, Nousiainen, & Rekolainen, 2008; Drechsel, Cofie, & Danso, 2010; Faerge, et al., 2001; Gumbo, Savenije, & Kelderman, 2002; Neset, Bader, Scheidegger, & Lohm, 2008). 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 (Han, Li, & Nan; Nilsson, 1995; Tangsubkul, Moore, & Waite, 2005). Beyond the effects of food systems, industrial ecology research has demonstrated the importance of non-food materials in urban material budgets (Decker, Elliott, Smith, Blake, & Rowland, 2000; Matsubae-Yokoyama, Kubo, Nakajima, & Nagasaka, 2009). Most of these non-food materials have not previously been incorporated into urban nutrient budgets, but may represent significant fluxes and stocks 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. The social (e.g., safety regulations) and biophysical (e.g., climate) drivers that regulate P dynamics through the urban food systems may differ from those for the built environment, which emphasizes the importance of including the latter in urban nutrient studies. I include both in the Phoenix, AZ 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 while in reality fluxes and stocks occur over *space* and may differ in magnitude and rate across the landscape. This spatial heterogeneity can have a major impact on how nutrient stocks 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. When P production and P needs are not co-located or evenly distributed across the landscape, there may be a reduction in P use efficiency that limits opportunities for nutrient recycling because this cycling is often mediated by transportation and energy costs. The spatial patterns of nutrient use, production, and storage are therefore fundamental to their sustainable management. A spatial understanding of nutrient cycling could allow for more nutrient-centric urban planning, where sources and sinks are co-located to maximize recycling. I consider the spatial distribution of P stocks and flows here in order to make better recommendations on the range of P-management options that may be appropriate for Phoenix.

I quantified the stocks and fluxes of P in Central Arizona-Phoenix Long Term Ecological Research site (CAP) in Arizona, USA (Fig. 1) and explored the distribution of dominant stocks and fluxes of P in the landscape for the Year

2005. I investigated P dynamics for the entire metropolitan region as well as among the soil, vegetation, water, animal, and material (e.g, paper) components of desert, urban and agricultural subsystems that make up Phoenix. In this chapter I address the following research questions: 1) What are the magnitudes of major fluxes and stocks across the ecosystem boundary and among subsystems? 2) What is the spatial arrangement of P movement and storage in the urban ecosystem? 3) Can I link major P fluxes and stocks to social, technological and biophysical characteristics of the study system? The synthesis of this information is framed relative to the sustainable management of P at the urban ecosystem scale.

Methods

Study Area

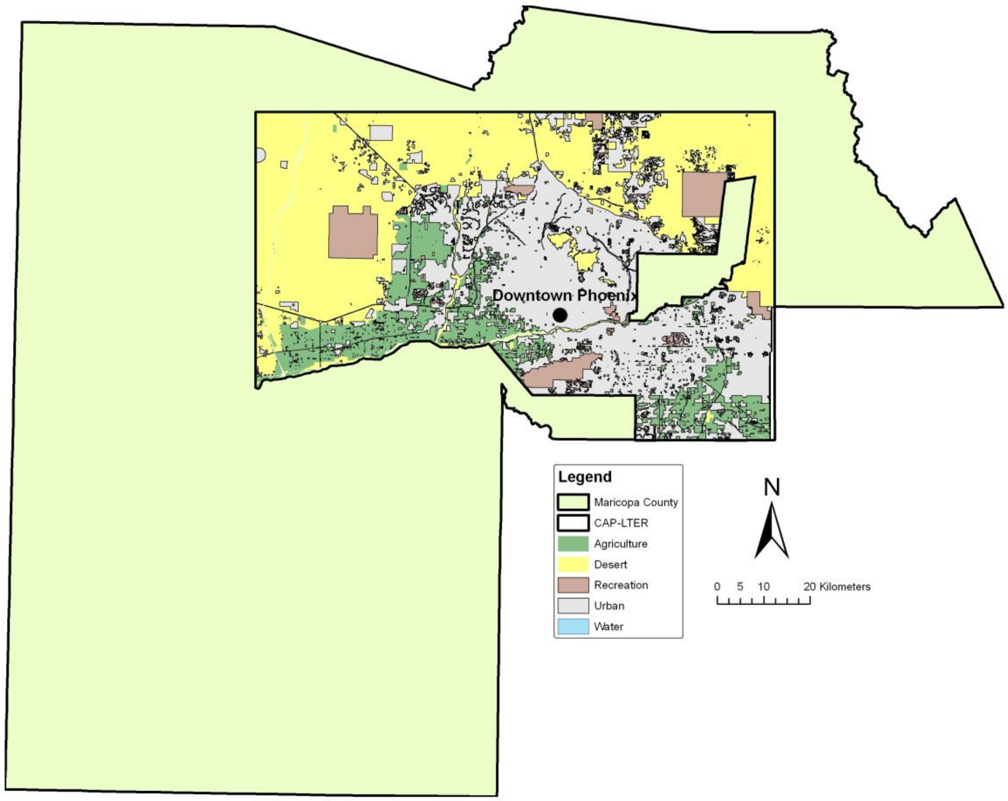

figure 1. Boundaries of the Central Arizona Phoenix Long Term Ecological Research site (CAP) ecosystem with in Maricopa County. The black boarder indicates the boundaries of the CAP system. Agricultural, desert, recreational, urban, and water land-covers are indicated in color (see legend) and the Phoenix downtown area is indicated by a dot as a reference point. The white area is Indian reservation land not included in the CAP study area.

The CAP ecosystem focuses on a 6,400 km^2 region in the semi-arid 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 CAP ecosystem has a population of about 4 million people and until recently was one of the most rapidly growing urban areas in the United States (Jenerette & Wu, 2001). The majority of the CAP study area 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. Urban land uses account for approximately 25% of the 6400 km^2 area (Stefanov, Ramsey, & Christensen, 2001). 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.

I included in the study system the atmosphere (up to the troposphere) and the soil (down to 30 cm depth), except where asphalt covers the soil, where I only considered the first 10 cm of asphalt (I did not consider where buildings cover soil). These boundaries were selected to include major soil stocks of P for which there adequate data exist as well as stocks in the built environment (asphalt) and fluxes of P from the atmosphere. As an arid city, water availability is a major concern, and 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 & Trapido-Lurie, 2006).

I used a three-pronged approach to understanding P cycling in the CAP ecosystem. First, I used a mass balance approach to estimate both human and natural fluxes of P into, from, and within CAP and identified the subsystems that drive the major fluxes. Then, I estimated major stocks of P in the biosphere, geosphere, and built environment. All fluxes and stocks were estimated for total

P, unless otherwise noted in the methods. Finally, I 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 CAP: sources of the major fluxes, which materials hold the most P, and where P is located across the landscape. I then used measures of accumulation and throughput to explore what these dynamics may mean for managers.

Mass Balance Approach

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

Mass balance studies traditionally only consider fluxes of nutrients. While stocks and flows 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 stocks. Because I was interested in implications for sustainable P management, the locations of large stocks were also important for this study. Stocks may be sources of P that are recycled within the system. I estimated stocks of P in soils, vegetation, animals, and the built environment. Although I was not able to estimate all possible stocks 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, I describe my approach for calculating fluxes to and from each subsystem and stocks of P within each subsystem. Detailed assumptions, data sources, and calculations can be found in Appendix A. I estimated fluxes using the following general equation (equation 1):

Equation 1: P Flux (Gg/yr) = mass of material / year * P concentration of material

I estimated stocks using the following general equation (equation 2):

Equation 2: P Stock (Gg) = standing mass of material * P concentration of material

P stocks and fluxes were computed using data from 2005, or the nearest available date. CAP-specific data were used for P concentrations and material stock and fluxes whenever possible. If data explicit to the CAP area were not available, I used the next best available data. In the rare case where no data were available, fluxes were calculated by balancing inputs and outputs (thus assuming steady state).

Atmosphere.

Dust containing P is wind transported from distant ecosystems (Field, et al., 2009; Neff, et al., 2008), representing an input to the entire CAP ecosystem. Both dust and particulate matter from fossil fuel burning are also produced within the boundaries of the study area and may be redeposited within the system or carried away via wind. I used wet and dry atmospheric data from CAP long-term ecological research (CAP LTER; 2005) to estimate total inputs of P as wet and dry atmospheric deposition (Lohse, Hope, Sponseller, Allen, & Grimm, 2008). I 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, 2005) and an average P concentration in gasoline emissions (Rand, 2003). Deposition may be highly variable based on precipitation.

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. I assumed that dust formation is negligible and did not include it in the budget. I categorized soils as mesic residential, xeric residential, non-residential urban (industrial and commercial areas), desert, and agricultural (Kaye et al. 2008). Chemical fertilizer and manure inputs to agriculture and residential soils were estimated from USGS fertilizer use reports (Ruddy, Lorenz, & Mueller, 2006), assuming that the ratio of chemical fertilizer application for CAP was the same ratio between total harvested area in Maricopa County to the harvested area in CAP (USDA, 2007). Estimates of P in runoff from soils and other surfaces were from(Fossum, County, & Survey, 2001). I 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 & Grimm, 2007). Due to data limitations I was not able to estimate storm runoff as a variable in this analysis (although I note that the CAP LTER Program is now intensively sampling stormwater runoff). I assumed that a negligible amount of P applied to surface soils (e.g., fertilizer) is transferred to groundwater via infiltration, because of high rates of evaporation and low rates of infiltration minimizing the movement of P with water. Stocks of bioavailable P in soils were estimated using CAP LTER data per (Kaye, et al., 2008).

Water.

Water enters the CAP ecosystem through precipitation, surface water from the Salt, Verde, and Colorado Rivers; and groundwater, carrying with it dissolved and particulate P. Once within the CAP ecosystem, much of this 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 from precipitation events carries P from soils to surface water.

Water leaves the CAP ecosystem as surface water to the Salt and Gila Rivers or is used to recharge groundwater.

Water fluxes were calculated using several methods. For surface water, water quality and discharge data from the USGS were used to calculate average annual fluxes from 2000-2005 using the mid-point method (Baker et al., 2001). For P fluxes, related to internal water allocation to agricultural, residential, and industrial users, I created a water budget using water use data (USGS, 2005) and water delivery data (MAG 2005). Water chemistry data from municipalities (City of Tempe, personal communication), state agencies (Arizona Department of Environmental Quality (AZDEQ), personal communication), and CAP LTER research (Water Monitoring Project, http://caplter.asu.edu) were then used to estimate P fluxes. To calculate fluxes of P in reused effluent, I used data on wastewater effluent allocation (Lauver et al., 2001), effluent P concentrations from CAP LTER research (Water Monitoring Project, http://caplter.asu.edu), and biosolid allocation and P concentrations from ADEQ records from 2005 (AZDEQ, 2006).

Vegetation.

I divided vegetation into xeric residential, mesic residential, urban non-residential, desert and agriculture categories to estimate and visualize stocks and fluxes. The CAP ecosystem includes a wide variety of vegetation including native desert species, xeric and mesic landscaping, and agricultural crops. All vegetation takes up P from the soil. For simplicity I 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 (namely dairy cows) or humans, or exported for processing (e.g., cotton).

I estimated stocks and flows for each non-agricultural vegetation type (shrub, tree, grass, other) in the CAP ecosystem. Fluxes of P through vegetation were estimated using carbon (C) flux data (net primary production) calculated for the Year 2000 (McHale, personal communication) and P concentration data for dominant urban and desert plant species from the literature (see Appendix A). I 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 (e.i., allocation to roots, leaves, and stems of desert shrubs, trees, and grass). It was not possible to estimate P uptake by lawns from NPP data, and thus I assumed that lawn uptake was equal to P lost in yard trimming collection in mesic landscapes (i.e. stock was steady state). Stocks of P in vegetation were estimated using vegetation biomass data for the CAP ecosystem (Melissa McHale, personal communication) and P concentration values from the literature (Freeman & Humphrey, 1956; Lajtha & Schlesinger, 1988; Meyer & Brown, 1985; Muthaiya & Felker, 1997; Williams & da Silva, 1997).

Agricultural uptake was estimated as the amount of P in harvested crops, in addition to uptake by woody crops like citrus, which were estimated using rates of NPP. Due to data limitations I could not calculate P uptake by non-woody crops to estimate the return of crop residues to soils. Harvest was calculated using crop production data from the U.S. Census of Agriculture for Maricopa County (2007). These production values were applied to the CAP 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 details). Removal of P as harvested crops goes to local human food supply for consumption, to feed to dairy cows, and to export. Because of data limitations I could not calculate gross fluxes (i.e., actual amount exported and imported) of agricultural commodities. Instead I looked at net fluxes of agricultural products to the region, and thus assumed that all edible crops were consumed locally (this is consistent with assumptions made by Baker et al. (2001) for their N budget of Phoenix). The same net flux method was assumed for feed production; however, I know that the majority of feed, primarily alfalfa, is in fact produced locally (United Dairymen Association (UDA), personal communication). Cotton is the only crop I considered as a net export, as processing does not happen locally. Cotton lint only contains trace amounts of P, and thus it is the export of cottonseed for oil production that contributes to P exports from this component of the agricultural sector (Unruh & Silvertooth, 1996). I assumed annual steady state for agricultural vegetation and constant standing stocks for orchards over the one-year study period.

Animals.

Pets.

I consider cats and dogs only, as these are the predominant pets in Phoenix. Pet food is imported from outside of CAP, and I assume that the majority of excreta goes to urban soils. I did not include estimates for wild animals because these fluxes are likely to be quite small. I obtained data on cat and dog populations from (Baker, Hope, Xu, Edmonds, & Lauver, 2001); personal communication) and nutritional needs and waste production of dogs and cats from the literature (Baker, Hartzheim, Hobbie, King, & Nelson, 2007). Stocks of P in cat and dogs were estimated using a P content value of 1%, which is the same as humans because no specific information on other mammals was available (Harper, Rodwell, & Mayes, 1977).

Livestock.

The major livestock in CAP is dairy cows. Approximately 40% of the milk produced in CAP is consumed locally; the remainder is exported from the CAP ecosystem (UDA, personal communication). Inputs of feed, namely alfalfa and grains, are also produced locally. I assume 100% of manure 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, Seay, & Baker, 2009) and American Society of Agricultural Engineers (2004). The stock of P in dairy cows was estimated using average P content value of 1% (Harper, et al., 1977). Fluxes of P through other livestock, including poultry, cattle, calves, horses, and ponies, were not included since these fluxes are negligible for the CAP ecosystem (USDA, 2007).

Humans.

Food for human consumption is both locally produced and imported into the CAP system. I assumed that all vegetables, fruits, and grains that were produced within CAP and not used for livestock feed were consumed locally (net flux assumption). I calculated P consumption using US per capita P consumption rates (NASS, 2003) and 2000 population data from census blocks within the CAP boundary (US. Census Bureau, 2000). Food waste along the food supply chain from groceries to households is approximately 50% (Lundqvist et al., 2008), therefore I assumed food inputs were double the amount of food consumed (Lundqvist, de Fraiture, & Modenm, 2008). Most food waste ends up in landfills and wastewater (via garbage disposals; MAG, 2005). Phosphorus from food that is consumed eventually makes its way to wastewater and septic systems (Drangert, 1998). I 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 (MAG 2002). The stock of P in humans was estimated using average P content (Harper, et al., 1977) and the population in the CAP boundary in 2000 (U.S. Census Bureau, 2000).

Material Environment.

Humans import products high in P such as cardboard, paper, wood, and textiles that accumulate in the city and landfills or leave CAP for recycling (World Resources Institute, 2007). Estimated fluxes of these materials to landfills and recycling were obtained from municipal trash analyses (MAG, 2005). Phosphorus concentrations were obtained from the literature (paper and wood; (Antikainen, Haapanen, & Rekolainen, 2004); textiles, (Yang & Yang, 2005). Humans also use materials in building and road construction that have relatively high P concentrations, such as concrete and wood. I did not calculate the stocks and fluxes of P in all of these materials due to the lack of available data. To calculate the stock of asphalt, I used remotely sensed data on land cover from Buyantuyev et al. (2007) to estimate the area of asphalt and assumed an average depth of 10 cm (Golden, Chuang, & Stefanov, 2009). Phosphorus content for asphalt from the literature was used to estimate stocks (Golden, et al., 2009). Stocks of P in other materials, including landfills, were not estimated due to the lack of available data.

Analysis of the P budget

In order to better understand P dynamics in the system using the calculated P fluxes and stocks at the ecosystem scale, I 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 shows what is driving the demand for inputs, producing outputs, or both. This is important to direct priorities in management both over space and by sector. Accumulation of P occurs when inputs to a system are larger than the outputs. Accumulation of P (sinks) may correspond to P hotspots in the city landscape. Hotspots are areas that are potentially vulnerable to eutrophication. These hotspots may also present areas of opportunity for sustainable management through the exploitation of high P concentrations as an input to other subsystems. I calculated throughput and accumulation according to the following equations (Equations 3 and 4):

Equation 3: Throughput (Gg/yr) = all inputs to the subsystem (Gg/yr) + all outputs from the subsystem (Gg/yr)

Equation 4: Accumulation (Gg/yr) = all inputs to the system or subsystem (Gg/yr) – all outputs from the system or subsystem (Gg/yr)

Additionally, I 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 CAP ecosystem boundary. Outputs for each subsystem were also calculated as the sum of all outputs from a subsystem (total outputs) and as the sum of all outputs that left the CAP ecosystem or entered a landfill.

Spatially Corrected P budget

The spatial budget was used as an exploratory mechanism to visualize the areal distribution of P stocks, inputs, and outputs across the urban ecosystem. The stocks and flows of the P budget were matched 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 I refer to as land classes (see appendix A for which P stocks and flows were matched to which land classes). The land classes were taken from several datasets, including: 2000 census tract data (U.S. Census Bureau, 2000), 2005 CAP land cover data (Buyantuyev 2007**)**, agricultural data from USDA (NASS 2010), 2000 land use data (CAP-LTER 2007), and dairy farm data (Goggle Earth 2011). All data were the latest available that encompassed all of the CAP study area. Each land class dataset was resampled to a 90 m^2 pixel resolution to maintain similarity among datasets. ArcGIS was the primary tool to create land classes that required the intersection of two or more datasets. For all stocks, inputs, and outputs, the total P value was uniformly applied across the relevant pixels. This was calculated by dividing the total P value associated with the land class by the number of 90 m^2 pixels encompassed by the land class. All data sets were clipped using a mask that represented the CAP study area and we used natural breaks for each map in the color scheme used to represent the concentration of P over the CAP landscape.

Uncertainty

Quantification of uncertainty is a concern for ecosystem mass balance studies. I used a combination of literature data and site-specific data to create the budget estimates. My calculations, data sources, and assumptions have been made explicit within the chapter and are available in detail through supplemental materials (see appendix A). I placed special emphasis in this chapter on the transparency of the data sources, assumption, and the limitations of my calculations. I provide a semi-quantitative analysis of uncertainty that will permit replication and discussion about how the results can be used for nutrient management applications.

Results

Fluxes

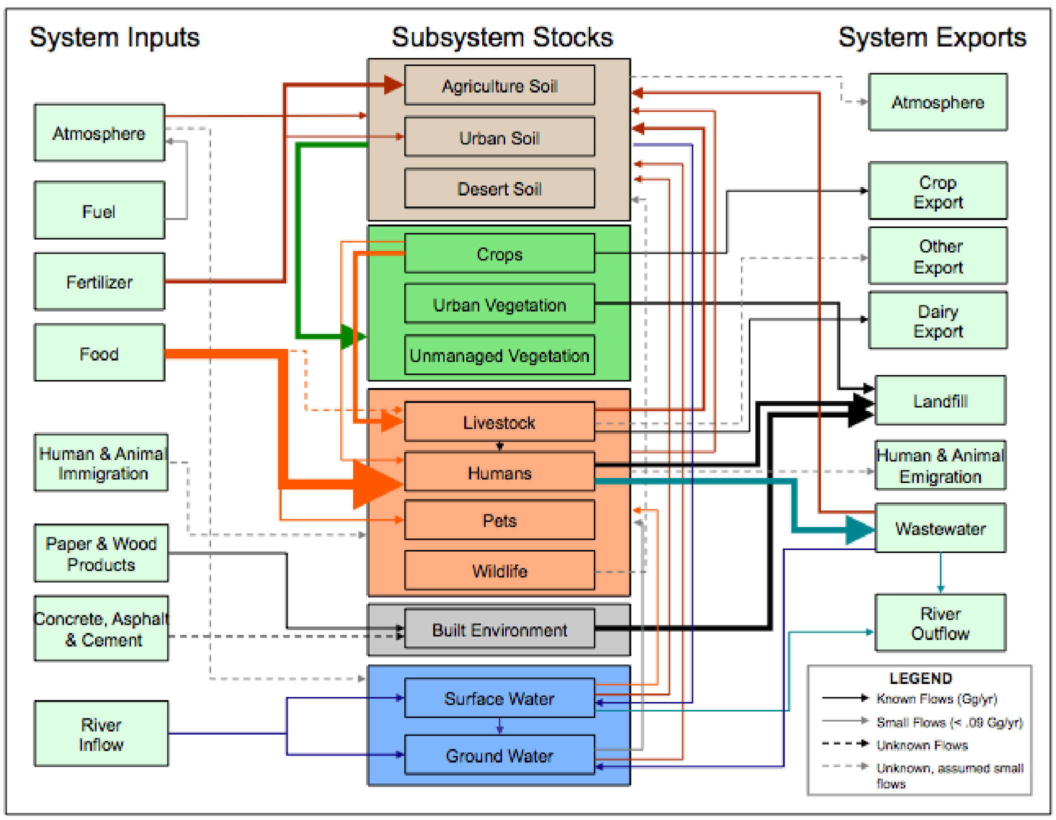

Figure 2. 2005 Central Arizona Phoenix Phosphorus budget. Central boxes are subsystem stocks (e.g. soil, vegetation, animals, water). Arrows are flows into and out of the CAP ecosystem or between CAP subsystems; arrows are sized relative to the magnitude of the flow and colored based on the subsystem they enter; grey arrows are small flows (< 0.09Gg/yr); dashed arrows are unknown flows; grey dashed arrows are unknown, and assumed small flows.

The CAP urban ecosystem is a net P sink (inputs > outputs). The largest P input to the CAP ecosystem is fertilizer to agricultural soils representing 43% of inputs, followed by food imports for human consumption representing 32% of inputs (Fig 2, Tables 1 and 5). The total P outputs from the ecosystem are more than an order of magnitude smaller than total inputs to the ecosystem. The largest P outputs from the CAP ecosystem include products to be recycled (e.g. paper from recycling bins exported for processing outside CAP), river outflow, wastewater treatment plant effluent, and dairy products (Tables 4, 2 and 6). Many of the largest fluxes are completely internal to the ecosystem and represent recycling of P within the CAP ecosystem. The largest internal fluxes include human waste to wastewater treatment facilities (Table 5), feed crops to cows (Table 3), the application of manure from local livestock to agricultural soils (Table 4), and the recycling of wastewater and biosolids for agricultural irrigation and fertilization (Table 1).

Water is an important vector for P transport in most systems (Bennett, et al., 2001). In CAP, runoff from urban land cover represents a small flux of P from soils and the built environment to surface water (Table 2). In reality, this flux may be even lower than my 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 approximately 60 km downstream of the 91st avenue sewage treatment plant are considerably lower

(0.11 Gg P/yr), indicating that this river may be a significant sink for P. Other subsystems will be discussed in the context of stocks, accumulation, and throughput.

Table 1
Soil Subsystem.

Components	P flux (Gg/yr)
Chemical fertilizer to agricultural soils	1.6
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	0.3
Atmosphere to soils	0.27
Yard trimmings to soils (compost	0.2
Groundwater to soils	0.03
Runoff	-0.44

Table 2

Water Subsystem.

Components	P flux (Gg/yr)
Sewage discharge to water treatment plants	2.74
Surface water inputs (Gila, Salt, and Verde Rivers, and CAP canal)	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
to urban system	0.008
Groundwater recharge	
from surface water	-0.02
from wastewater	-0.09
Surface water outputs	-0.11
Wastewater to soil (biosolids)	-1.67
Wastewater to soil (effluent irrigation and septic)	-1.83

Table 3
Vegetation subsystem.

Components	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
Non-residential 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 4
Animal Subsystem.

Components	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 5

Human Subsystem.

Components	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 water	-1.95

Table 6

Material Environment Subsystem.

Components	P flux (Gg/yr)
Paper and cardboard import	0.3
Paper and cardboard to recycling	-0.06
Textiles to landfills *	-0.1
Other waste to wastewater	-0.45
Paper and cardboard to landfill[b]	-1.13

*No data about textile imports available

[b] No equivalent import data

Stocks

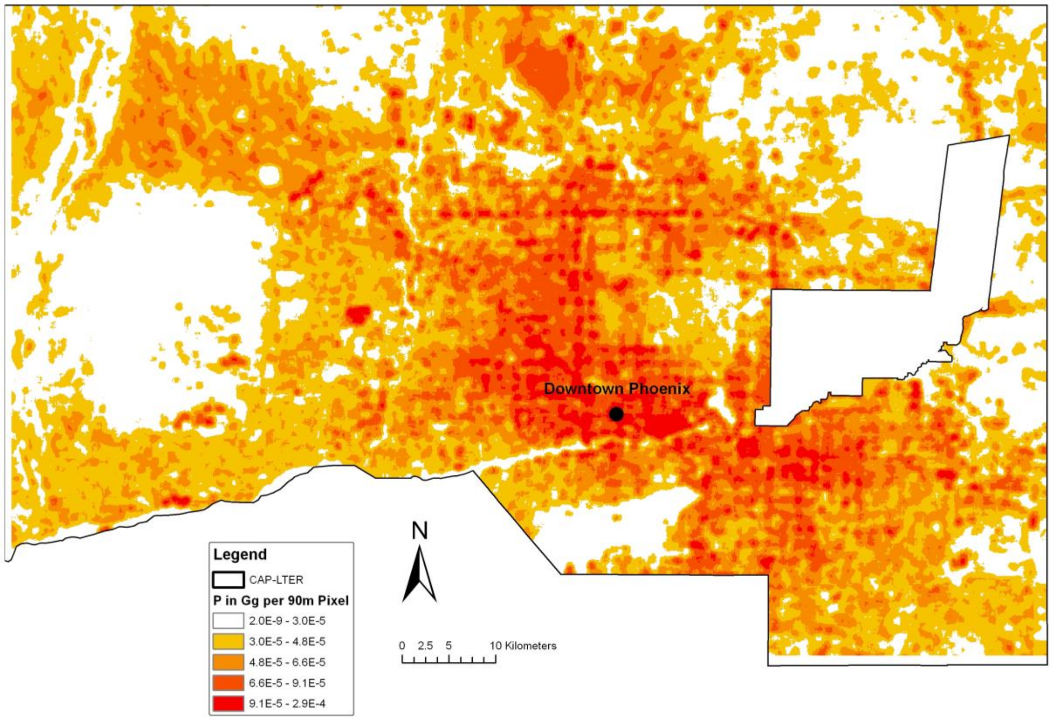

Figure 3. Spatial Distribution of stocks across the CAP ecosystem. Phosphorus is concentrated in densely populated areas where patterns of streets are visible because of P in asphalt. Stocks included are vegetation, soils, asphalt, dairy cows, humans, and pets. Image was smoothed using focal statistics with a 5 cell radial filter.

Soils dominate P stocks, representing 55% of total stocks, followed by asphalt, vegetation, and humans (Table 7). Although accumulation of P in desert soils is considerably less than in agricultural and urban soils, desert soils account for the most soil P storage because the CAP ecosystem is 50% desert land cover.

Stocks are most concentrated in areas that have been altered by humans. The street pattern of the Phoenix metropolitan area is clearly visible in the map of

P stocks in CAP (Fig. 3), indicating that asphalt is a major contributor to the distribution of P in the CAP landscape. Human population density also shapes the concentration of P stocks. Humans have a high P content, and also influence their immediate environment. 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. Agriculture land use is visible, as agricultural P stock is an important, if not a dominant, feature (see Fig 1 for land use distribution).

Table 7
Phosphorus stocks in the CAP ecosystem.

Known Stocks (2005)	Total Gg of P	Area (m^2)
Desert Soil	8.45	278,5217,400
Asphalt	7.25	298,258,200
Agriculture soil	4.2	697,369,500
Desert vegetation	4.18	713,682,900
Xeric residential soil	3.9	772,626,600
Humans	3.2	-
Xeric residential vegetation	1.96	772,626,600
Cows	1.9	68,080,500
Mesic residential soil	0.82	380,845,800
Mesic residential vegetation	0.46	380,845,800
Urban non-residential soil	0.4	768,519,900
Urban non-residential vegetation	0.15	768,519,900
Pets (cat and dogs)	0.1	-
Agriculture vegetation (Tree crops)	0.07	7,160,400

Accumulation and Throughput.

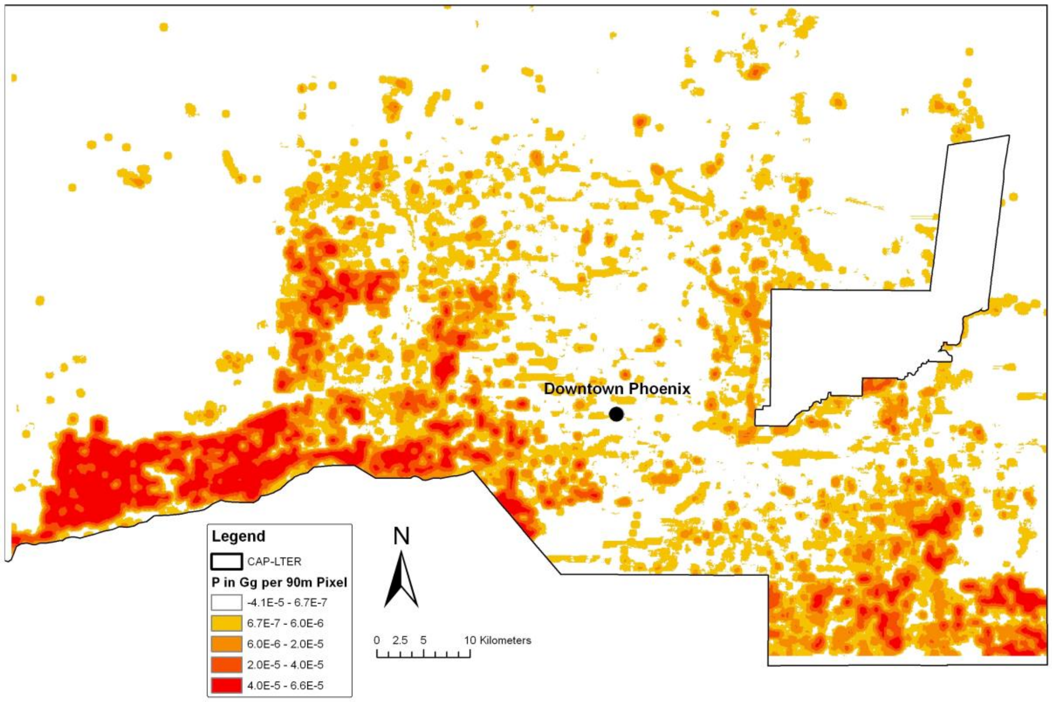

Figure 4. Spatial distribution of accumulation of P in the CAP Ecosystem. High accumulation (input-output) occurs in agricultural areas. Note that this accumulation is for each $90m^2$ cell. Fluxes included in maps are atmospheric deposition, humans, pets, food, agricultural products, organic waste, and fertilizer.

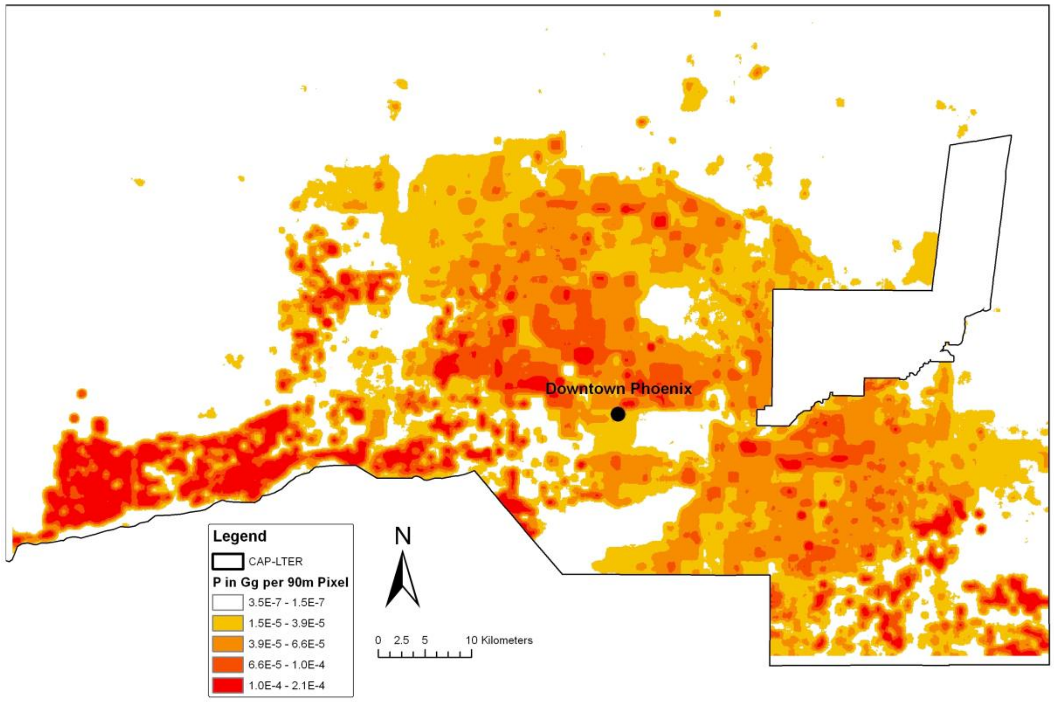

Figure 5. Spatial distribution of throughput in the CAP ecosystem High throughput (input+output) occurs in agricultural and urban area. Note that this is throughput is for each cell. Fluxes included in maps are atmospheric deposition, humans, pets, food, agricultural products, organic waste, and fertilizer.

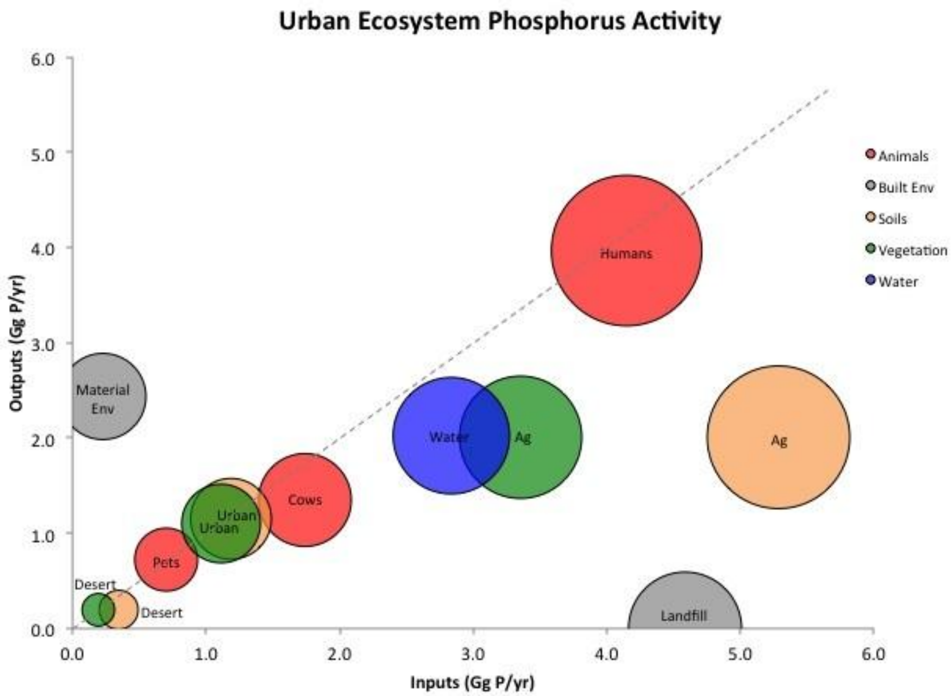

Figure 6. Inputs and outputs of P to and from subsystems. Circle color indicates subsystem domain (vegetation, soil, water, animal, built environment), and circles size indicates throughput (input+output). The dashed line is a 1:1 line representing an equal amount of inputs and outputs. Subsystems below the dashed line accumulate P, while subsystems above are sources of P.
Note: The location of the "Material Env." circle is to the far left should be interpreted with caution because different sources for input and output values were used here which may have resulted in some inconsistencies (see Appendix A).

I calculate that the CAP ecosystem accumulated 1.73 Gg of P in 2005. This accumulation took place primarily in agricultural soils (Fig. 4 and Table 1). I did not include landfills in Figure 4 P accumulations since many are located outside CAP boundaries. However, they are located within Maricopa County (where CAP is also located) and do represent an important long-term sink (4.59 Gg P/yr). Landfills receive large fluxes of P from yard trimmings and residential organic waste. Also not visible on the map of P accumulation are fluxes related to water. However, due to inputs of high P wastewater effluent, surface water, and withdrawals of low P groundwater, the groundwater aquifer represents a net sink for P, accumulating 0.07 Gg P/yr.

At the subsystem level, animals (including humans) had the largest throughput followed by agricultural vegetation, driven by crop harvest (Fig. 5 and Table 8). This hierarchy of throughput was also visible on the landscape, where throughput was high in areas with high human densities, agricultural production, or dairy production (fig. 5). In general, subsystem throughputs were either net sinks for P or are nearly balanced inputs and outputs (outputs = 0.4958 (inputs); R^2=0.1301). Larger throughputs (i.e. agricultural soils, agricultural vegetation, human, and water) were generally net sinks for P, whereas subsystems with lower levels of system throughput were distributed along the line representing inputs = outputs (Fig. 6). This pattern was also visible in Figure 4, where crop and dairy production areas had high accumulation per pixel. The built environment subsystems (i.e., material environment and landfills) had a markedly different distribution from animals, soils, vegetation and water, although the location of the built environment circle may be a result of data limitations (see Appendix A). Although urban soils had relatively lower throughput, they were accumulating a high proportion of its P inputs. The domination of P fluxes by agriculture and humans (through the production and consumption of food and the production of waste) demonstrated the importance of the food system to urban P dynamics. The spatial (fig 4 and 5) and subsystem approaches (fig 6) both attested to the importance of P fluxes related to food, and how throughput and accumulation were related but still presented distinct patterns.

Table 8

Characteristics of subsystems in CAP. Expressed in Gg or Gg/yr.

Subsystem	Input	External Input	Throughput	Accumulation	Output	External Output[a]
Soil	6.8	2.1	10.2	3.5	3.3	0
Water	2.8	0.1	4.9	0.8	2	0.2
Vegetation	4.7	0	9.7	1.4	3.3	0.9
Animal	2.4	0.1	4.5	0.4	2.1	0.1
Human	4.1	4	8.1	0.2	4	1.7
Material Environment	0.2	0.2	2.7	-2.4[b]	2.4	2.4
Landfills	4.6	0	4.6	4.6	0	0

[a] Considers waste to landfill as an external output

[b] negative accumulation is due to lack of data on inputs to the system

Discussion

The Budget and landscape of Phoenix

The CAP urban ecosystem is a net P sink. Humans control the movement of P through the importation and production food, recycling of water, and management of solid waste. That said, 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 P accumulates in the system and how CAP, as the ecosystem of Phoenix, may differ from other city P budgets. The distribution of subsystems which have no natural ecosystem analog (notably the material environment, landfills, and agriculture, and humans) according to their inputs and outputs of P is very different from those subsystems similar to natural ecosystem components (fig. 4). Taken as a whole, the distribution of throughput and accumulation values of subsystems in the CAP urban ecosystem is distinct and supports the concept of a distinct urban biogeochemistry developed in Kaye et al. (2006).

The role of agriculture and water.

The importance of agricultural and food related fluxes was apparent in both the budget approach and the spatial approach (Fig.4 and 5). Eighty percent of imports were related to the food system and most internal fluxes were transfers along food production-consumption chains. For example, the dairy system accounted for inputs of fertilizer for alfalfa, transfers of feed to cows, eventual local consumption, and waste production. This portion of the chain is quite linear and is similar to our global understanding of anthropogenic modifications of P cycling (Childers, et al., 2011; Cordell, 2010). However, there were large internal fluxes that included the application of manure, biosolids, and wastewater on agricultural lands that represented recycling among human, livestock, water, and soil subsystems. CAP P dynamics appeared more cyclical than linear because of these large recycling flows (Fig. 2). High P organic waste that was not recycled tended to contribute to the accumulation of P in landfills or soils.

A large portion of the recycled flows, accumulations, and outputs from the CAP system were related to water management. The modification of local hydrology, such as effluent recycling, occurs in response to concerns about water scarcity yet it plays a major role in internal P cycling, such as when wastewater is applied to agricultural fields. (Lauver & Baker, 2000) showed that the regional focus on water availability and subsequent water management decisions impacted the CAP/Phoenix nitrogen cycle in similar ways. Apart from deliberate water recycling, local hydrology also plays an important role in limiting the risk of eutrophication associated with concentration of 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 or infiltrates belowground before reaching surface water bodies (i.e. the Salt River). Stormwater engineering, such as retention basins, further limit downstream fluxes. The deliberate management of water resources, and the natural cycling of water should be considered in how to best manage the urban P cycle in CAP.

The material and built environment.

Stocks and fluxes are linked through accumulation, but are not distributed in the same spatial pattern. In CAP, fluxes were dominated by agricultural production and animal food consumption, whereas the largest P stocks were associated with dense human populations (Fig 3). These stocks however, may not be easily recycled on short-time scales. For example, P bound in asphalt is not easily recycled, especially compared with stocks in urban vegetation. Such differences influence short- and long-term management opportunities. In addition, stocks in the built environments were at some point imports to the system and outputs from the system through demolition and could potentially represent a source of P for reuse on long time scales. As with the built environment, the stocks and flows associated with materials (e.g. paper and textiles) had a markedly different distribution from animals, soils, vegetation and water stocks and fluxes.

Ultimately, stocks and fluxes associated with the built environment are driven by consumption patterns that are sensitive to economic conditions. Even though I was not able to calculate them, fluxes of construction materials such as concrete are undoubtedly substantial in this ecosystem, especially during periods of rapid growth. Considering that rapid urbanization has characterized Phoenix for many years, it seems certain that P in the built environment is accumulating, but a better understanding of how construction and demolition affect P dynamics spatially is important for the management of P resources. In particular, the spatial visualization illustrated that large stocks in the budget do not always translate into concentrated deposits of P that could be recycled or "mined" as a P supply (e.g. desert soils were a large stock of P, but this was a low concentration over a large area and is thus unlikely to be a viable source of future P; Table 7). Managing material stocks and fluxes so as to encourage and enhance P recovery and productive recycling should be a priority for both scientists and practitioners; this requires further spatial and technological research.

Efficiency and other metrics of P management.

Increasing P use efficiency in CAP would require minimizing external inputs to the CAP ecosystem and waste stream outputs from the system by decreasing flows through subsystems and increasing recycling. By decreasing external P inputs, we can decrease reliance on mined P resources, increasing urban P security, and subsequently food security (and stability in other processes that use P). However, an overall decrease in inputs and outputs does not necessarily indicate a more sustainable P system. The goal is to decrease inputs without decreasing population or standard of living. This requires efficiently managing inputs and outputs, but more so requires increases in internal recycling.

The current contributions of subsystems driving inputs from outside the CAP ecosystem and contributing to exports outside the ecosystem or to sinks of P not easily recycled (waste stream outputs) suggests that P management should emphasize P efficiency in the human, vegetation, and material environment subsystems because they produce large amounts of solid waste that accumulates in landfills or is exported to other cities (Table 8). The strong accumulation of P in agricultural soils, as well as the high throughput of local agriculture, animal husbandry, and humans (because of their eating habits) shows how the food system dominates P fluxes in the CAP ecosystem. The food system may thus be the most vulnerable subsystem to concerns about eutrophication and P security. We should thus focus on how to reduce external inputs and outputs from components of the food production system. CAP currently has a number of large recycling flows (Fig. 2), but the effectiveness of such recycled flows at decreasing the need for external inputs remains uncertain because the recycling of nutrients is a by-product of other management strategies. In general, external inputs, external waste stream outputs, the degree of internal recycling, accumulation, and throughput together are important metrics for managing P more sustainably.

Uncertainty.

Decision makers must often act without perfect information, and the level and type of uncertainty plays a role in how managers use information about P cycling in planning for the future (Oenema, Kros, & de Vries, 2003). I identified five types of uncertainty in the budget: measurement uncertainty, human observer error, biogeochemical uncertainty (uncertainty about when and where P is binding to other compounds), resolution limitations (both temporal and spatial), and data availability. Some forms of uncertainty may be reduced with the collection of additional data and application of new methods (e.g., different manipulation of spatial data). Other sources of uncertainty, especially in urban environments, are more difficult to reduce. A better understanding of these types of uncertainty (by both researchers and policy makers) and more transparency about uncertainty is necessary to enable informed decisions. I posit that understanding uncertainties about P recycling and P accumulation are the most critical in CAP, due to the importance of these fluxes for management decisions and the magnitude of their contribution to the urban P cycle. In particular, the ultimate fate of P in wastewater, biosolids, manure, and fertilizers remains unclear due to local conditions that may limit bioavailability. And there is uncertainty about the accumulation of P over space and in time due to the heterogeneity of human application of P (fertilizer or other). Both the ultimate fate of P and heterogeneity of P on the landscape contribute to the effectiveness of current recycling strategies and the efficiency of external P-input use.

These areas of uncertainty are important avenues for future investigation and I suggest that future research on urban nutrient budgets be done in partnership with practitioners (e.g., wastewater treatment plan officials, construction companies, city offices) to both reduce uncertainty when possible, and ensure a better understanding of inherent uncertainties. Managers have access to data sources and knowledge that are not available to the public and can fill data gaps. For example, filling data gaps about the built environment would require more transparency from government offices that regulate and finance infrastructure projects, as well as from private contractors. A better understanding of urban P dynamics is important but not sufficient to increase the sustainability of P management. The explicit involvement of city managers and other practitioners that directly affect P cycling in research would facilitate the creation and implementation of effective P-management plans because these managers would better understand results and thus facilitate a transition towards positive change.

The usefulness of visualization of P stocks and flows.

The spatial correction of the urban P cycle permitted us to scale stock and fluxes of materials available at other scales than that of the CAP ecosystem to the CAP boundary. This ability decreased the number of estimations about P cycling using different system boundaries that were necessary with a non-spatial approach because of data gaps. For example, instead of using Maricopa County data as a proxy for agriculture in the CAP area I was able to apply data about crops and fertilizers in Maricopa County on land-use layers and then only use the proportion that applied to the CAP ecosystem. In this way, the visualization of P stocks and flows increased both the understanding about the concentration and dispersion of P in the environment and refined the aggregate understanding of subsystems in the non-spatial budget. I suggest that urban nutrient budgets include a spatial component to better refine understanding of nutrient cycling in cities.

Connections, trade-offs, and needs for future work

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 strongly across cities. In Bangkok, Thailand 59% of P inputs accumulate within the system (Faerge, et al., 2001) while Gälve, Sweden accumulates 67 % of its P inputs (Neset, et al., 2008) and CAP/Phoenix accumulates 86 % of its P inputs. 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). Mesic cities with high proximity to water, such as Gälve and Bangkok, have higher outputs than Phoenix (Neset, et al., 2008) (Faerge, et al., 2001). The Phoenix P budget is more comprehensive than many other urban budgets because it includes many 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 the 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 and waste management technology), wealth (as it affects diet), and human population size.

Recommendations for Management.

City managers should consider using nutrient budgets to think holistically about a system when making decisions, particularly budgets like this one that comprehensively include important stocks and flows, as well as spatial distribution. As mentioned earlier, the management challenge is to decrease P imports while maintaining food security and other benchmarks of quality of life to sustain a healthy population. One way to do this is by increasing the efficiency of plant P uptake (Ramaekers, Remans, Rao, Blair, & Vanderleyden, 2010; Yang, et al., 2007). The existing land-use heterogeneity in CAP could also be better utilized to recycle waste to serve as P inputs in landscape and agricultural soils. Smaller scale, decentralized strategies would minimize transportation costs and thus lower the cost of recycling. It is critical that recycling be used to match P needs. Much recycling of P currently in CAP is inadvertent, and therefore inefficient. A strategic P-management plan would restructure recycling to maximize P bioavailability while taking advantage of existing recycling infrastructure to meet goals for water and waste management.

The myopic management of resources, including nutrients, can lead to inefficient solutions and serious trade-offs that may only be apparent in the future. Increasing understanding of urban P dynamics, as I do here, is a necessary first step, but because nutrients do not cycle in isolation it is insufficient to manage for a single nutrient (Sterner & Elser, 2002). As technologies, regulations, built structures, and economies change and develop, so does the relationship between resources. The circumstances that lead a city to be a strong sink or source of nutrients are strongly contingent on land-use patterns and other socio-economic drivers and are likely to change substantially over time. Our spatial budget can serve as a first time point to explore how, as such factors change through time, the distribution and concentration of P changes in the CAP ecosystem. If population continues to grow (a source of P) and agriculture continues to shrink (a sink for P) I posit that Phoenix will become less of a sink for P. The city will need to import more P as food and will have less opportunities for recycling P through wastewater, manure, and organic matter recycling to agricultural soils. In order to holistically understand and manage urban P, I must further examine the relationship between resources (e.g., P, N, C and water) and continue to explore future scenarios. 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.

Conclusion

The CAP ecosystem accumulated 6.02 Gg of P in 2005 (including landfills) and known stocks sum to 38 Gg. Inputs were dominated by direct food import and fertilizer for local agriculture, while most outputs were small and included water, crops, and materials destined for recycling. Internally, fluxes were dominated by transfers of food and feed from local agriculture and the recycling of human and animal excretion. The spatial representations of P dynamics showed that human density and associated infrastructure and landscape, especially asphalt, dominated the distribution of stocks in this urban landscape, while fluxes were dominated by agricultural production. Both human (infrastructure, technology, and societal norms (e.g., landscaping decisions)) and biophysical characteristics (soil properties, water fluxes, and storage) shape urban P dynamics. These P dynamics are different from non-urban ecosystems, and support the findings of Kaye et al. (2006) about a distinct urban biogeochemistry. In CAP, concerns about water availability and the characteristics of the arid ecosystem are important in shaping the strong accumulation of P in the system. The importance of both deliberate human decisions that mediate P movements within CAP, and the features of CAP's arid landscape shaping the P cycle means that they both must be considered when deciding how to manage P to increase sustainability.

On the global scale, anthropogenic P cycling is dominated by food production (90 % of mined P is used for fertilizers), but at the ecosystem level there are also other important stocks and fluxes. As with other urban P budgets, I identified the food system as a key subsystem, but recycling opportunities may exist in this city and others through other urban material flows such as detergent or P used in steel production (Decker, et al., 2000; Matsubae-Yokoyama, et al., 2009). It is clear by the variation across urban P budgets that local context must be considered when creating a sustainable, coupled nutrient resource management plan. Still, data about the material environment need to be more widely included in urban budgets in order to better understand its potential for improving P management.

Global and local nutrient cycles are altered by human whether we mean to or not; however, active and intentional management of nutrients is needed to address both supply and waste issues. To address both issues we must move from an open or linear system, where P is lost to waterways or non-recoverable location, to a closed system, where P is tightly cycled by efficient recycling within the system (Childers, et al., 2011). Furthermore, interactions between nutrients and other critical biophysical processes mean that trade-offs and synergies may exist between efficient management of nutrients, water, and energy at local and global scales. CAP P dynamics could easily become linear if population increases and agriculture decreases. Alternatively, P flows could become highly cyclical if resource conservation and co-management of resources were implemented, perhaps in the pursuit of decreasing city dependence on external resources. Thus, deliberate, linked management strategies for P and other resources should be a priority for cities in achieving urban sustainability.

Chapter 3

PHOSPHORUS CYCLING AT THE URBAN-AGRICULTURE INTERFACE OF MARICOPA COUNTY

Introduction

The link between phosphorus, agriculture, and cities

Phosphorus (P) is an essential nutrient for plants, and all living organisms, and is often the limiting nutrient in agricultural soils (Chapin, et al., 2002; Drechsel, Gyiele, Kunze, & Cofie, 2001; Pierrou, 1979; Runge-Metzger, 1995). Modern agricultural systems depend on mined P for fertilizer to maintain high crop yields and the production of fertilizer is the most important cause for human alteration of the global P cycle (Smil, 2000; Turner, 1990). Of the 160 million tons of phosphate rock we currently extract a year, 90 % is for fertilizer production, making agriculture, and the food chain that follows, not only the most important agent of change in global P cycling, but also vulnerable to uncertainty about mineral P availability (Cordell, et al., 2009).

As urban environments increasingly dominate the landscape, it becomes increasingly important to understand how P moves through or cycles within urban ecosystems. Cities are thought of as P sinks, with food being the most important source of nutrient flow into cities (Chapter 2; Drechsel, et al., 2010; Faerge, et al., 2001). Moreover, there is still a large amount of agriculture in and around many cities. This agricultural production accounts for most of the inputs of fertilizer and feed to cities (Drechsel, Graefe, & Fink, 2007; Faerge, et al., 2001; Gumbo, et al., 2002; Neset, et al., 2008; Nilsson, 1995). The food system in its entirety, from production to consumption and treatment of waste (human and animal), is one of most important contributors to urban nutrient cycles, including P. Researchers and practitioners alike need to better understand urban agricultural dynamics because the agricultural component of cities is key to how urban environments both contribute to global problems of P availability and how they can contribute to solutions to linear P cycling (Gumbo et al., 2002; Cordell, 2010). Phosphorus availability and cycling are crucial factors in urban and agricultural sustainability (Guzy, Smith, Bolte, Hulse, & Gregory, 2008; Thapa & Murayama, 2008).

The limitations of static nutrient budgets in understanding phosphorus dynamics

Nutrient budgets are often used to understand P cycling in ecosystems, including urban systems. However, these budgets are often static analyses that consider stocks and flows for only a point in time (e.g. one year). This snapshot approach, although useful, cannot fully elucidate the mechanisms that shape the nutrient dynamics of an urban ecosystem. Nutrient budgets have limited utility as tools for decision making about nutrient scarcity and eutrophication because the mechanisms underlying P cycling operate over time and space and at different scales. Thus, we need to consider nutrient budgets in relation to cross-scalar problems and drivers of change over time to understand P dynamics and make future recommendations (Scoones & Toulmin, 1998). To understand how the urban-agriculture interface plays a role in sustainable P management, we must first understand how this interface has changed over time, how these changes have affected P cycling, and why these changes took place.

Objectives

This chapter presents an analysis of changes in P cycling at the urban-agriculture interface of Maricopa County, Arizona, which encompasses the Phoenix Metropolitan area (Fig. 7), from 1978 to 2008. I focused on P fluxes in the production of alfalfa and cotton, the two most important crops by acreage in the county. I have four objectives in this chapter:

1) Use annual time-series data to explore changes in P dynamics in the Maricopa County urban-agricultural system over the specified study period.

2) Identify the major divers of change for P dynamics in the urban agricultural system of Maricopa County over the study period.

3) Compare an average P budget for Maricopa County to the global agricultural P budget presented in Cordell, et al (2009) and Childers, et al. (2011) in order to explore the importance of local biophysical and economic factors in shaping urban agricultural P dynamics in Maricopa County.

4) Identify opportunities for intervention to enhance sustainable management of P resources at the urban-agriculture interface of Maricopa County.

Methods

Study area

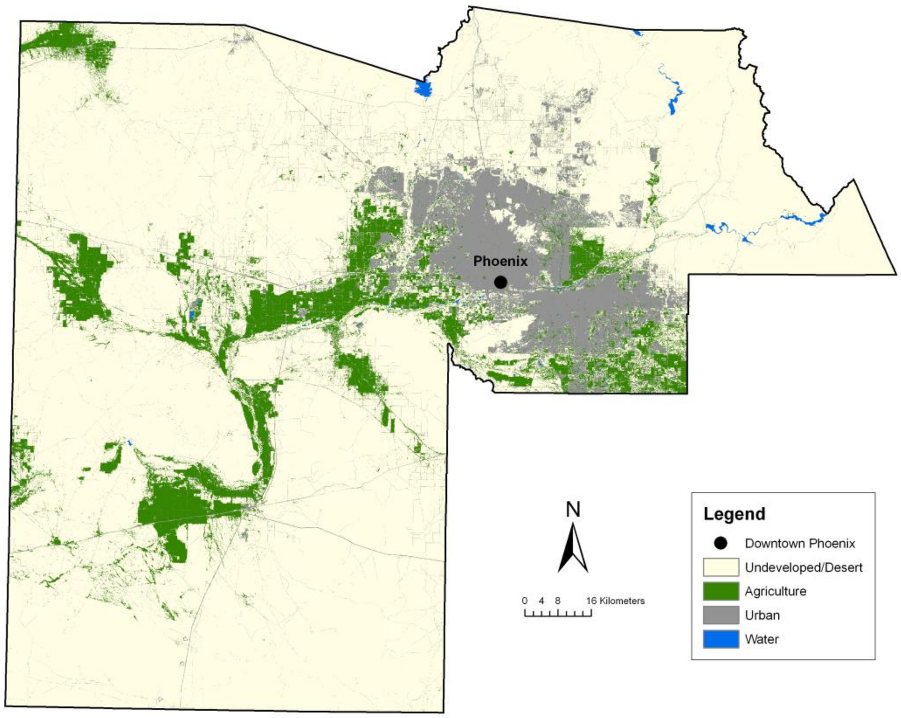

Figure 7. Map of Maricopa County, including a delineation of agricultural and urban land-uses, with the location of water sources and the downtown Phoenix area used as reference points. Source: NASS 2010.

Maricopa County is located in south-central Arizona, covers 23,836 km^2, and receives an average of less than 8 inches of rain annually. Agriculture has been present in this region since the first prehistoric human settlements in the area and is now part of the urban mosaic of Phoenix (Fig. 7). Between 1980 and 2008, the population of Maricopa County increased from 1,509,052 people to 3,958,263 people, mostly in the Phoenix Metropolitan area (Frostall, 1995; U.S. Census Bureau Population Division, 2010). This population growth (until 2008) coincided with dramatic urban sprawl, often on agricultural lands. Urban fringe agricultural land was often bought for development and the right to use water associated with agricultural land for urban use. This phenomena explains the relatively high price of agricultural land compared to the Western-US region as a whole (NASS, 1999, 2009), but this trend has slowed since the recession (Eden, et al., 2008). Agricultural production has persisted in Maricopa County, but with important changes in character. One of the more important changes has been a shift from cotton to alfalfa production over the past several decades, in part because of increased local dairy production (Frisvold, 2008).

The desert environment has both a long growing season and high rates of evaporation and evapotranspiration. The latter requires intensive irrigation of farm fields. Alkaline calcareous soils, commonly called *Caliche* soils, dominate the landscape. These soils have large $CaCO_3$ nodules that easily trap phosphate, making it more difficult for plants to access P (Holloway, et al., 2001; many U.S. agricultural cooperative extension reports).

The Phoenix Metropolitan area is a strong sink for P, accumulating 89% of annual imports (see Ch. 2). The Phoenix P budget, as with other published urban P budgets (see introduction), shows that P cycling is dominated by human and animal food production and consumption (see Ch. 2). The import of fertilizer and food accounts for 80% of imports, and the cycling of food, feed, and organic waste from the consumption of these products accounts for the majority of internal fluxes according to the Phoenix P budget of 2005 (see Ch.2).

Projects to increase water conservation and recycling in Phoenix appear to have affected local N and P cycling (Lauver & Baker, 2000 and Ch.2). The addition of treated urban wastewater to groundwater supplies and recycling of treated urban effluent back to irrigation (which mostly ends up in agricultural soils) have created large recycled nutrient flows (e.g., 0.92 Gg of P) within the system (Ch.2). In addition, solid waste is recycled though the application of biosolids to cotton and other crops production (1,67 Gg of P in 2005, Ch.2; Lauver & Baker, 2000). Thus, the agricultural system of Maricopa County is not only a dominant subsystem of Phoenix P imports and exports, but also responsible for most of the intra-city P recycling. Although P recycling is for the most part an unintended consequence of the management of water and resources, the management of said resources are essential considerations in exploring the sustainability of P cycling in the area.

Mass Balance Budget approach

I used a mass balance budget method to calculate the flows of P in the Maricopa County agricultural system from 1978 to 2008. This budget approach was the same that was used to create the P budget for the entire Central Arizona Phoenix area (Ch. 2), and the N budget of Phoenix (Baker, et al., 2001). I conceptualized the agricultural P subsystem in terms of flows that enter and exit Maricopa County and flows of P between components of the agricultural and urban domains (Fig.8). I could not construct complete annual P budgets because of data gaps. I thus examined changes over the years where data were available for each P flow (arrows in Fig. 8). I subsequently constructed an average P budget using value ranges based on the years where data were available for each flow. I used this average urban-agricultural P budget to compare P dynamics at this scale to a global agricultural P budget. The following sections detail how I calculated flows:

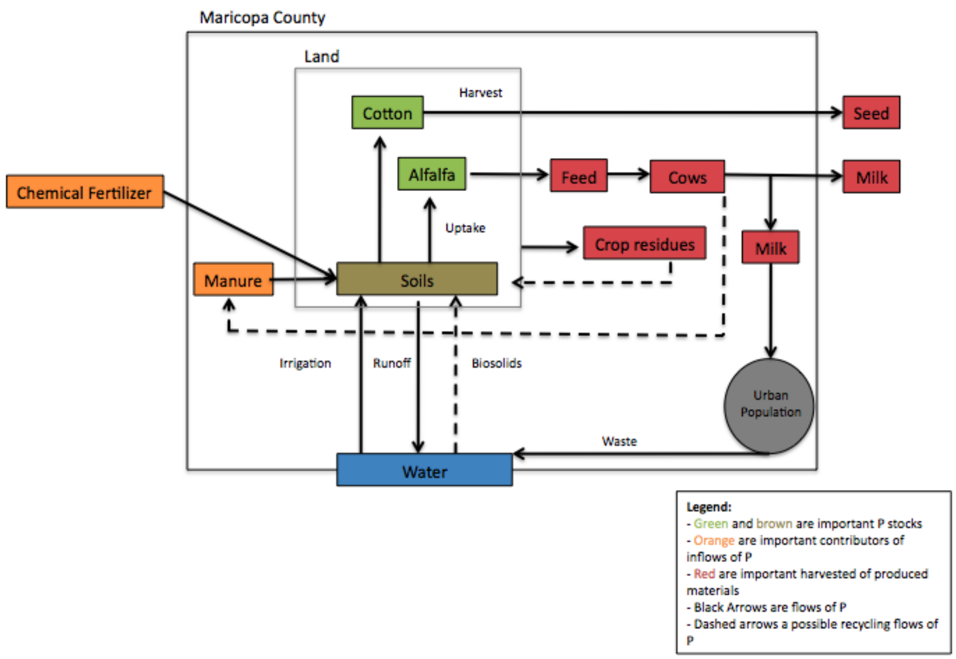

Figure 8. Conceptualization of the phosphorus agricultural system of Maricopa County.

Fertilizers.

Inputs of P to the agricultural system were dominated by chemical fertilizer purchases. Chemical fertilizer and manure application from livestock production within the county were the major inputs to agricultural soils. I used data collected by the USGS on the amount of chemical P fertilizer purchased in Maricopa County for agricultural use on an annual basis (Alexander & Smith, 1990; Ruddy, et al., 2006). I assumed that all fertilizer purchased in a given year was applied to fields in that year. From 1978-1981, only state-level estimates of chemical fertilizer purchases existed. I scaled these to the county level by assuming the ratio of County to State harvested acres from 1978 to 1981 reflected the proportion of P fertilizer applied in Maricopa County. These estimates also included manure application. From 1982 to 2001, records of fertilizer purchases existed at the county level (Ruddy, et al., 2006). Ruddy et al. (2006) also presented a record of P applied as manure calculated every five years, assuming 100 % of manure produced in Maricopa County was applied to fields. Data on P application did not exist for 1986, or from 2002 to 2008 (USDA and USGS, personal communication).

Wastewater.

Biosolids, defined as the treated solid waste from wastewater treatment facilities, are typically applied to agricultural fields within Maricopa County. Although biosolids have been applied to fields since the 1960s in Arizona, only in 1996 did AZDEQ implement the Arizona Biosolids Program to comply with the U.S. Clean water Act (1977). This program requires permits for biosolid application (Artiola, 2006) and thus generates data relevant to my P budgets. AZDEQ records for the dry weight of biosolids applied to cotton and alfalfa fields were only available from annual records from 2005 to 2008 and I used the average P concentration in biosolids from AZDEQ annual reports as the multiplier to determine the annual P flow of biosolids to agricultural soils (AZDEQ, 2006; Artiola, 2006).

Soils and Water.

Little information on the P content of runoff or in soils exist. Because of minimal eutrophication risks, governmental agencies do not undertake large-scale standardized data collection efforts about the movement or storage of P in Maricopa County (USGS, U of A extension agency, USDA, personal communication). Because of high evaporation rates and relatively level topography, the assumption is that rainfall is unlikely to run off of agricultural fields (Dr. Silvertooth, Head of the Department of Soil, Water and Environmental Science, University of Arizona, personal communication). Dissolved and particulate sources of P transported in water from irrigation and precipitation events may be temporarily unevenly distributed over the area of a field but over a year would be redistributed through tilling. Even though the majority of rainfall in Maricopa County comes as monsoon events and thus there is probably some displacement of P in soils, I did not have data to quantify the impact of such effect on P distribution. The total P content of soils growing cotton and alfalfa is not publically reported, and thus I was not able to directly calculate the annual stock of P in agricultural soils or P accumulation in these soils. In addition, the arid climate of Arizona does produce dust storms and these events may also transport P from agricultural soils to other areas, but no data exist for this aeolian flux and I assumed it was not a significant factor in P movements (Dr.Zerkoune, Natural Resource Conservation Service, personal communication).

Cotton.

I calculated P harvested as cotton using data on the annual production of cotton lint from Upland (*Gossypium barbadense*) and Pima (*Gossypium hirsutum*) cotton cultivars in Maricopa County (USDA, 2007; USDA Arizona Field Office, 2011). However, there are only trace amounts of P in cotton lint (Bassett & Werkhoven, 1970; Unruh & Silvertooth, 1996), making cotton seed exports the most important source of harvested P for this crop. Data for the seed to lint ratio and seed P concentration were specific to Maricopa County but were not available on an annual basis (Anderson-Clayton Ginning Company, personal communication; Unruh & Silvertooth, 1996). The uptake of soil P by cotton plants was calculated using uptake values specific to Maricopa County as well (Unruh & Silvertooth, 1996). Cotton lint and seed are separated and processed at cotton gin facilities outside of Maricopa County; thus 100% of the P in cotton is exported. Most crop residues are left on the field and thus assumed to be reincorporated into local soils (Dr. Silvertooth, U of A, personal communication). (See Appendix C for the range of cotton P uptake and P concentrations applicable to Arizona.)

Alfalfa.

I calculated P harvested as alfalfa using the number of acres planted in alfalfa annually combined with average annual yields per acre in Maricopa County and with the P removed in harvested alfalfa based on annual yield from the USDA-NRCS online nutrient tool (using the removal coefficient for hay early bloom cut 1 alfalfa in the US and default moisture from this online tool; USDA Arizona Field Office, 2011; USDA & NRCS, 2000). Uptake of soil P by alfalfa was calculated as per Mikkelsen (2004). Most alfalfa remained within the County as the major feed crop for the local dairy industry—the most important type of livestock production in Maricopa County (UDA, personal communication). Thus, P in alfalfa was assumed to only be exported from the system as milk (See Appendix C for the range of alfalfa P uptake and P concentrations applicable to Arizona.)

Driving Factors

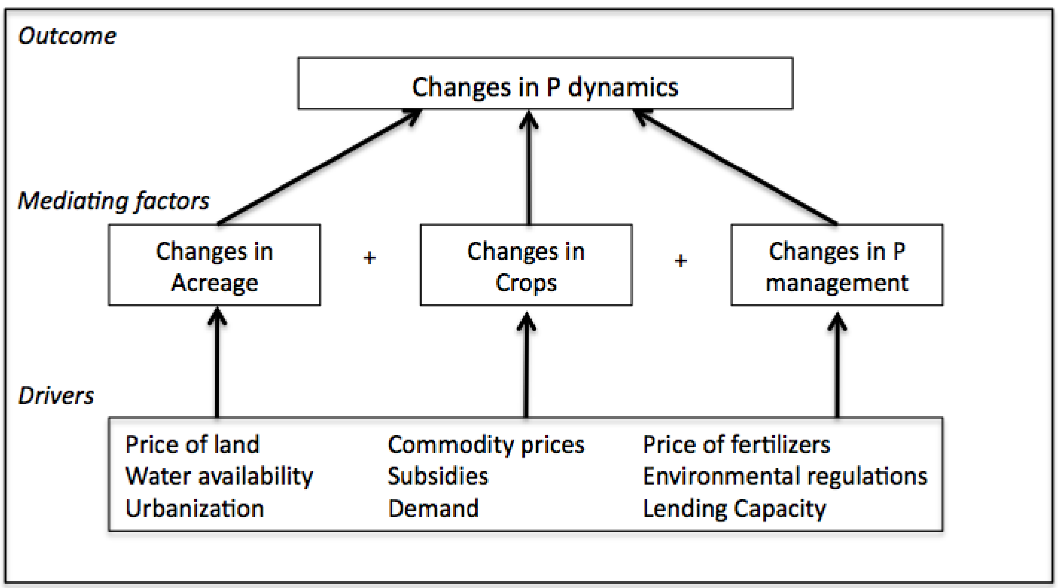

Figure 9. Drivers of change of Maricopa County urban-agricultural P dynamics.

The expansion of the Phoenix Metropolitan area, increases in national and international commodity prices, and government subsidy shifts (and other supporting institutions) have all contributed to agricultural change in Maricopa County (Judkins, 2008; Joe Sigg, AZ Farm Bureau representative, personal communication). These same factors are thus posited here to influence P cycling (Fig. 9). I obtained the average price of agricultural land annually from 1994 to 2008 for Maricopa County from NASS reports (NASS, 1999, 2009). These averages do not include Indian reservation land prices for rent or sale, which does have agricultural production on it. I obtained annual price data for cotton, alfalfa, and milk for Maricopa County from USDA-NASS Arizona field office records (2011). I obtained the price of chemical P fertilizer (expressed as the producer price index for P in the US to normalize for price inflation) from the NASS and the Bureau of Labor Statistics annually from 1978 to 2008 (NASS & BLS, 2010).

Interviews

Interviews were conducted in order to provide information that was missing from existing data sources and literature about the use and movement of P in the Maricopa County urban-agricultural system, and why this movement has changed over time. I conducted interviews with leading experts on Maricopa County agriculture as cooperative extension agents, academics, and farmer organizations. The interviewees were recommended by ASU faculty or by other key stakeholders during the interview process (snowball method). I also used Internet searches for relevant organizations to locate some interviewees. I received Internal Review Board (IRB) approval for both interview and survey protocols (see Appendix B for approval forms and interview questions).

Comparison of Maricopa County with the global agricultural system

I compared the P budget of the urban-agriculture interface of Maricopa County with the P budget of the global food system as a means to indentify key characteristics of the Maricopa County system that may influence the strategies that may be most effective to manage P better at the local scale. In other words, I wanted to identify which local characteristics were important in shaping P dynamics, that in turn may shape which management strategies were appropriate in that context. I used Cordell et al. (2009) Figure 3 as the global P budget for agricultural systems and used Childers, et al. (2011) global ranges of P flow values to contextualize the differences I observed. I used the same categories as the Cordell et al. (2009) paper to characterize the local Maricopa County agricultural system. I obtained single values for Maricopa County by averaging multi-year values for each flow, and gave ranges of available data. In order to compare local and global flows I normalized values by dividing flow values by the values of the chemical fertilizer flow from Maricopa County and global estimates respectively.

Results

Changes in phosphorus dynamics over time

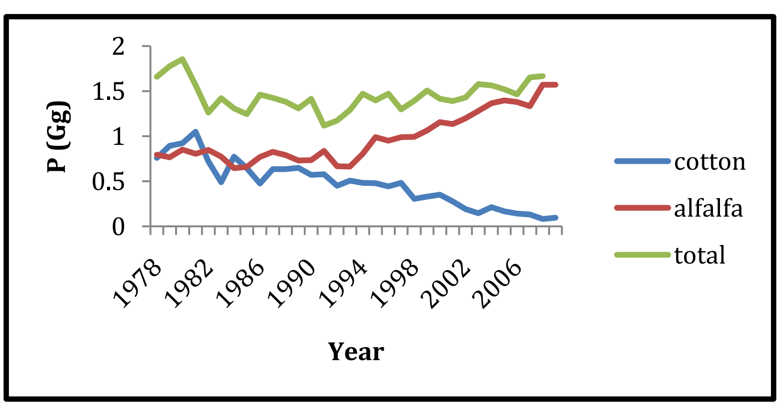

Figure 10. Harvested phosphorus in cotton and alfalfa production from 1978 to 2008 in Maricopa County.

Total harvested P in cotton and alfalfa in Maricopa County fluctuated between 1.12 and 1.85 Gg of but did not exhibit a substantial increasing or decreasing trend between 1978 and 2008 (green line Fig. 10). Internally, crop sources of P changed substantially. Alfalfa and cotton contributed almost equally to harvested P in 1978, but alfalfa accounted for almost all harvested P by 2008. This change had an effect on the proportion of P exported and internally cycled in Maricopa County because alfalfa was consumed within the boundaries of Maricopa County as feed for dairy cows. This milk production was both exported and consumed locally while the manure from these dairy cows was applied to local agricultural fields. Thus, the increased share of alfalfa production resulted in decreased P exports and increased internal P cycling.

Maricopa County's total agricultural acreage decreased 44 % between 1978 and 2007, and the number of acres that received fertilizer also decreased (Fig.11). Alfalfa is a more P-intensive crop in terms of harvest because it is harvested multiple times a year, whereas cotton is only harvested once. Thus, even with less land under agricultural production, an increase in alfalfa production resulted in relatively little change in harvested P. The average P applied as fertilizer fluctuated between 11 and 17 kg per acre, but with no substantial trend up or down in application per acre between 1978 and 2001 (Fig. 12). The relatively constant harvested P from cotton and alfalfa (green line Fig.9) with less land under production and minimal change in chemical fertilizer application can be accounted for if recycled P flows increased or if the efficiency (i.e., the outputs obtained per unit of input of P use) increased over time. Increases in P recycling ostensibly resulted from the increased manure and biosolids application enabled by the shift from cotton to alfalfa production in Maricopa County.

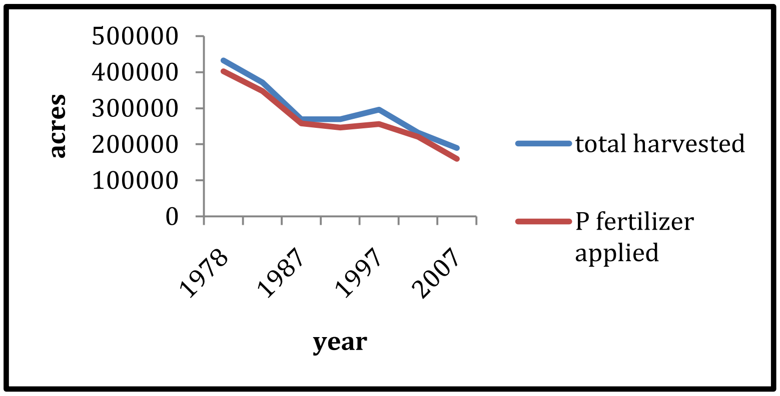

Figure 11. Total harvested acres in Maricopa County and acres to which fertilizer was applied from 1978 to 2007.

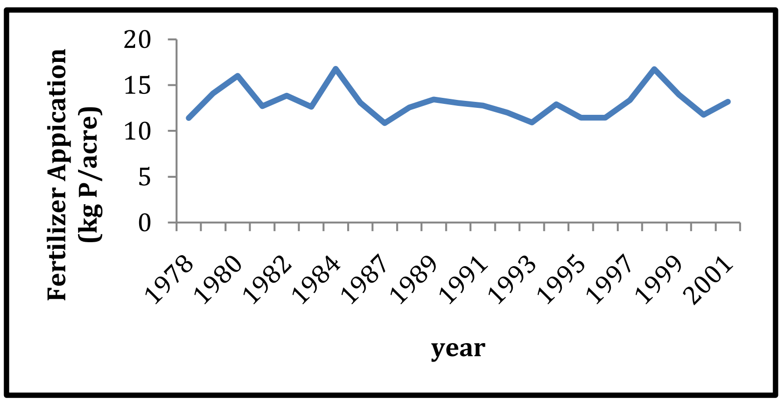

Figure 12. Phosphorus applied per acre. P applied as chemical fertilizer on known acreage receiving chemical fertilizer (1978 to 1982 include manure).

Drivers of change over time

Phosphorus dynamics were affected by changes in three things: acreage in agricultural production, the choice of crops planted on this land, and the way P, and other resources, were managed to grow these crops. These three mediating factors were affected by drivers which affected P dynamics and how these dynamics changed over time (Fig. 9).

As described in the previous section, acres in harvest have decreased over time (Fig. 11). The price of agricultural land in Maricopa County increased over three-fold, from US$ 810 to US$ 3500 per acre, between 1994 and 2008 (Fig. 13). After 2008, prices decreased because of the national economic recession and a consequent decrease in new housing construction projects that would drive the purchase of agricultural land.

The price of Pima cotton, although high, fluctuated significantly during the period of study until production was no longer recorded by the USDA in 1999. The production of upland cotton continued to be large enough to be recorded and, although at a lower price, price fluctuations were also large (Fig. 14). The price of alfalfa and the price of milk also fluctuated, but not to the same extent. From 2001 to 2007 the price of alfalfa rose steadily but then dropped precipitously in 2008 (Fig. 14). The large fluctuations in the price of cotton compared the smaller fluctuations and steady rise of alfalfa prices influenced crop production decisions and the consequent shift in the sourcing of harvested P to alfalfa (Fig. 9).

The shift away from cotton production was largely due to a drop in cotton prices nationally and internationally, lack of local agricultural lending capacity, and shifts in government subsidies (Judkins, 2008; Joe Sigg, AZ Farm Bureau representative, personal communication). Cotton is a capital-intensive crop with only one harvest a year; thus, a lack of easily available capital and highly fluctuating prices (see Fig. 12) were not ideal for income security. This explains a decrease in cotton production. The choice of alfalfa in particular to replace cotton was mainly motivated by increases in dairy production. Increases in alfalfa production over the past 30 years were in large part a response to increasing international demand for milk products, especially in Asia and Oceania. In the early 2000's, the New Zealand and Australia milk industries collapsed due to drought, which increased the amount of milk the two countries imported. Maricopa County producers increased their herds to meet this increase in demand (UDA, personal communication).

The price index of chemical P fertilizer remained stable until a sharp spike in 2008 (Fig. 15). After 2008, the price of P fertilizers dropped but not below 2007 prices (data not shown) (NASS & BLS, 2010). The relative stability of fertilizer prices during the study period probably suggested that P prices did not play a large role in nutrient management decisions or crop choice between 1978 and 2007. The fertilizer price spike in 2008, however, may have influenced decisions in 2008 and 2009, when farmers became more concerned about the management of inputs. Another factor influencing nutrient management was the decision of the EPA and USDA in 1999 to redefine confined animal feeding operations, so that farms over 200 cows became subject to nutrient management plans under the National Pollutant Discharge Elimination System permit regulation and Effluent Limitation Guidelines (Beegle, Sharpley, Weld, & Kleinman, 2005). These regulations specified that the application of manure be based on the limiting nutrient of local soil, which, in Arizona is often nitrogen (N). Application based on N requirements usually translates into over-application of P, as P does not have an atmospheric component to its cycle, unlike N. I was not able to calculate P accumulation in soils because of lack of data. Shifts in P dynamics at the Maricopa County urban agricultural interface seem to have been motivated by commodity prices which are a symptom of larger changes in national and international agricultural systems between 1978 and 2008, rather than direct changes in P fertilizer prices or new environmental regulation on nutrient management.

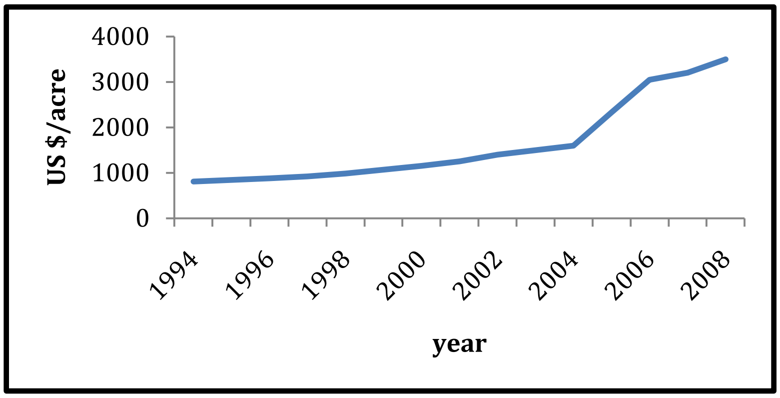

Figure 13. Price of farmland in Maricopa County from 1994 to 2006. Source: NASS.

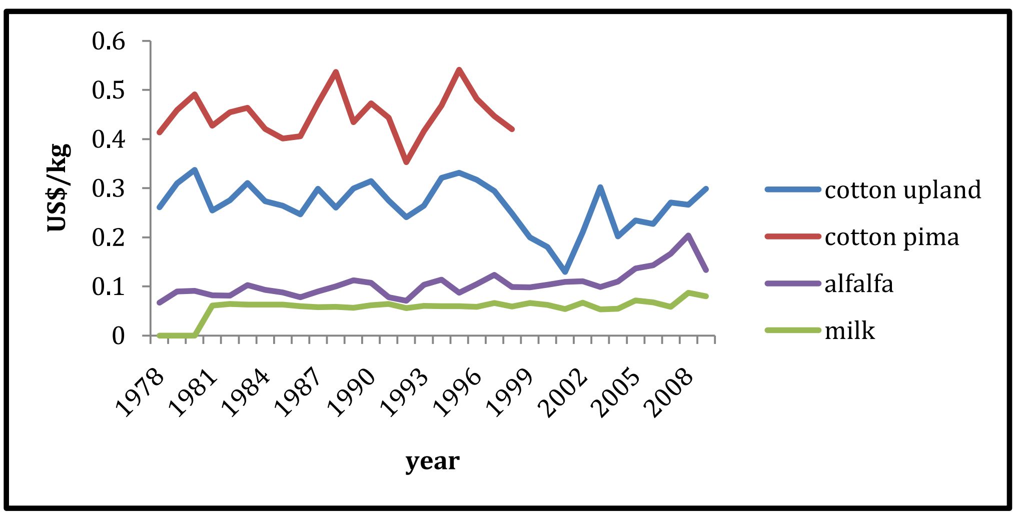

Figure 14. Changes in prices received by farmers in Maricopa County. Source: NASS.

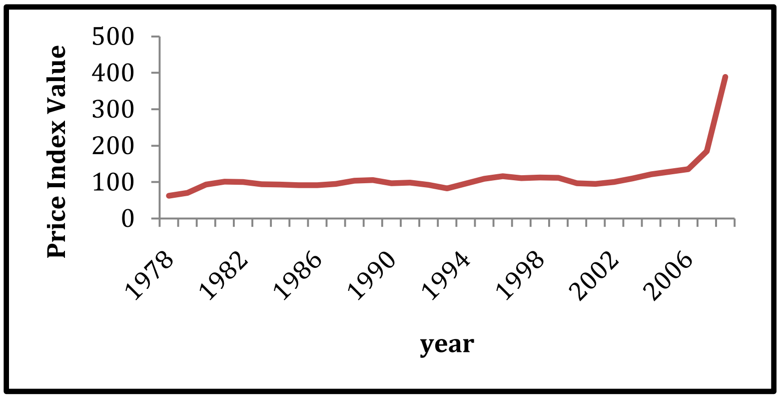

Figure 15. US phosphorus fertilizer prices from 1978 to 2008. Produced price index values are used here to illustrate fluctuations in the price payed by farmers for P fertilizers normalizing for inflation using 1982 as a baseline with a index value of 100 Source: NASS and BLS.

Maricopa County system and global comparison

The average P budget of the agricultural system of Maricopa County was used to explore the magnitude of P flows in the system. The comparison of the Maricopa County Budget to the global agricultural budget was used to indentify key features in the Maricopa County system that may make it different from P cycling in the global system and thus influence the management strategies that should be prioritized. The Maricopa County P budget indicated that chemical P fertilizer was the most important contributor to P in agricultural soils, as it was in the global agricultural system (Fig. 16 and Cordell et al., 2009). The proportion of chemical fertilizer application to P uptake by plants and P in harvested crops was similar at the global and local scales, suggesting that the efficiency of P cycling in Maricopa County agriculture was close to that of the global agricultural system (Fig. 17). Total inputs to soils were larger than uptake by alfalfa and cotton, so P should be accumulating in the system. But also, vegetable and grain crops, which accounted for 30% to 50% of harvested acres in the study period, that were not considered in this budget contribute to P uptake in Maricopa County. The allocation of P among animal feed, food commodities and non-food commodities is different between the Maricopa County and global P budgets. More P went to feed production in Maricopa County, while more P went to food production at the global scale. The Maricopa County system appeared to loose less P to runoff and recycle more manure than the global system (Fig. 17).

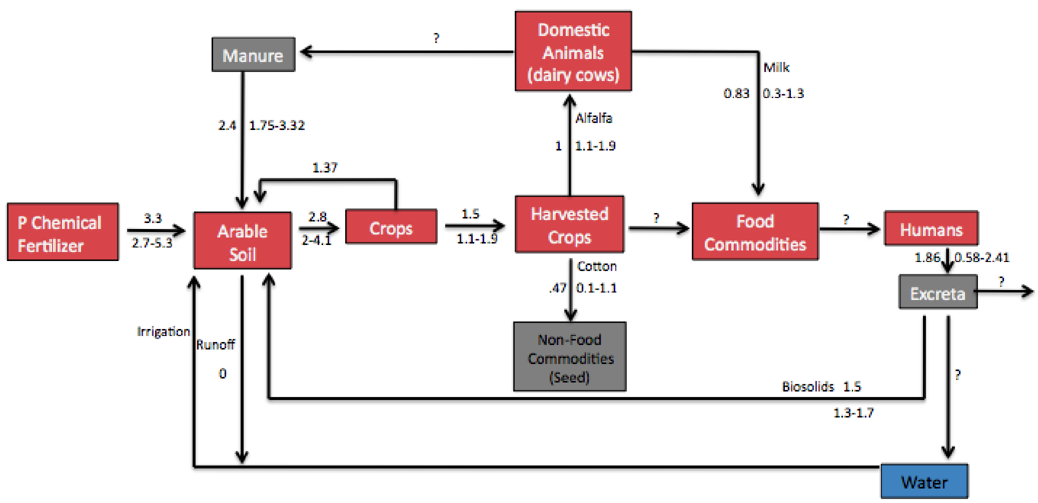

Figure 16. Phosphorus cycling at the Phoenix urban agricultural interface. The average value of P flows in Gg/yr are above arrows, and ranges of values available for each flow are below arrows.

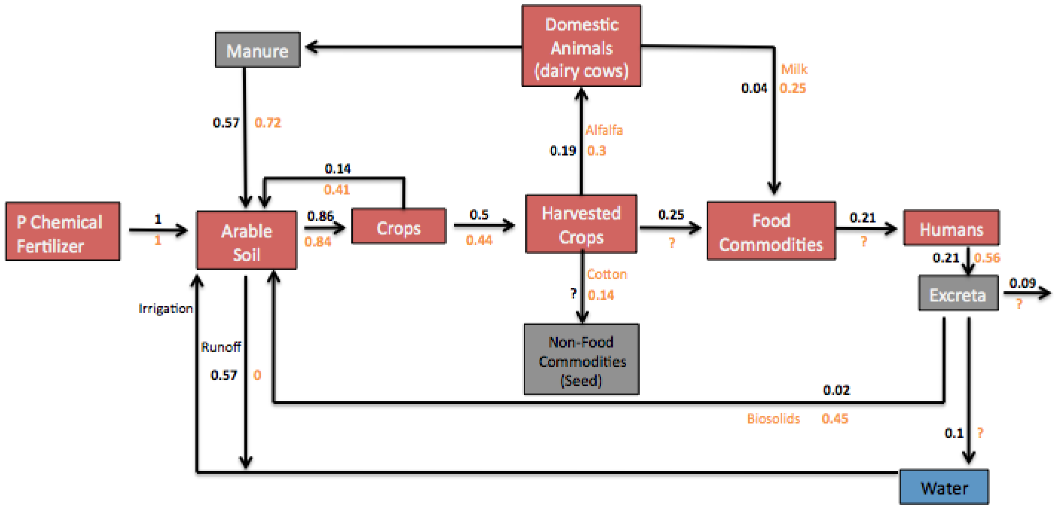

Figure 17. Comparison of phosphorus cycling between global and Maricopa County agricultural systems. Values are expressed as a ratio to chemical fertilizer inputs. Values in black are for the global system and yellow values are for the Maricopa County system.

Discussion

The relative contribution of drivers to changes in P dynamics

Between 1978 and 2008, harvested P from cotton and alfalfa production in Maricopa County did not substantially decrease (Fig. 10) in spite of a decrease in total acres harvested (Fig. 11) and a relatively constant rate of chemical P fertilizer application (Fig. 12). However, internal dynamics of P flows did change. Changes in crop choice seemed to be the main driver of these changes, as opposed to changes in acreage or P management strategies. Changes in macro-drivers affecting the availability and allocation of resources (especially capital) and the price of commodities appeared to explain the observed shift in crop production (Fig 14), and subsequent changes in P dynamics. Although it is usually assumed that urban expansion explains most shifts in agricultural production, these data as well as Judkins (2008) suggested that larger scale drivers were largely responsible.

How the dairy industry has influenced changes in the Maricopa County urban agricultural system

Dairy production has been an important part of Arizona agriculture since European settlement in the 19th century. The location of modern dairies in urban areas is likely a legacy of the perishable nature of dairy products; without refrigeration, dairies had to be located near consumers of their products (Davis, 1959). Dairies have been part of the urban agricultural interface since they were first established.

The close link between alfalfa, dairy production, and local dairy consumption strongly influences P cycling. The switch from cotton to alfalfa production increased P recycling in Maricopa County between 1978 and 2008. The geographic distribution of production and consumption of P ultimately determined the relative contribution of recycling in maintaining the relatively constant amount of harvested P in Maricopa County between 1978 and 2008 and in chemical P fertilizer application rates in Maricopa County between 1978 and 2001.

The co-location of livestock and feed production seems to have facilitated increases in nutrient recycling through the application of increasing amounts of manure on agricultural soils. Manure is a waste product that must be disposed of by livestock producers, and it is also a major source of nutrients for crop production, and thus their co-location facilitates recycling. However the distribution of manure on fields may not be proportionate to the P requirements of crops because EPA regulations require farmers to manage manure application according to N need in Arizona. In addition, areas around dairy farms often receive much more P than fields further away, because of prohibitively high transportation costs of moving manure, also resulting in the unequal distribution of P (Dr. Zerkoune, NRCS, personal communication). The uneven application of manure and focus on management of N may have resulted in over-application, and the subsequent accumulation of P in some soils.

The co-location of agricultural and urban land uses also enhances nutrient recycling. The application of biosolids from urban sewage treatment to alfalfa fields (although also applied to cotton fields) is part of a closed-loop system that links the consumption of dairy products back to the production of alfalfa and the subsequent production of more dairy products. As urban populations have increased, so has the recycling of biosolids that contain P. But, as with manure management, the application of biosolids is not managed according to P needs, but rather to minimize pathogens and metal contaminants in soils. Thus, we lack the spatial data and time-series data on P accumulation in soils necessary to determine whether our current recycling strategies use recycled-P effectively. It may be that increases in efficiency, or the use of existing P stocks, are responsible for the "constant" level of harvested-P between 1978-2008. Soil P content is the key unknown in this system. With better knowledge of soil P content we could determine whether chemical and recycled P is absorbed in the agricultural process or accumulating in soils.

Dramatic changes in 2008

In 2008, the price of fertilizer appeared to directly alter P management (Fig. 15). Available information suggested that dairy and alfalfa production decreased in response to the dramatic increase in fertilizer prices. Over the past 15 years, but accentuated after 2008, farmers have become more interested in more conservative P management strategies as an alternative to resist increasing input costs. For example, cotton farmers show interested more interest in cooperative extension work on P fertilizer recommendations based on yield response after 2008 (Dr. Silvertooth, U of A, personal communication).

To understand P cycling, it is important to look at how the dairy industry was affected by the economic recession of 2008. Dairies in Arizona remained profitable during the Great Depression because even though the price of milk was low, the input costs (e.g., feed and petroleum) were also low (Davis, 1959). In contrast, the 2008 crisis reduced the number and size of dairies in Maricopa County (UDA, personal communication). This was likely driven by a simultaneous decrease in international milk demand and prices, an increase in input costs (fertilizer and fuel), and a tightening of the credit market. In part this tightening may have occurred because of municipal interest to purchase farmland and the water rights associated with it (UDA, personal communication). These same pressures affected alfalfa and cotton production. Thus, although I have limited quantitative data with which to analyze the effect of large shocks on the agricultural system in 2008, it seems that these shocks may have impacted P cycling by both directly affecting P management and affecting other drivers of P cycling like commodity prices. Further research is required to evaluate the validity of this hypothesis.

The results of this study reinforce the need to better understand interactions across scales and across sectors (e.g., agriculture, waste management, water management) in complex socio-ecological systems. Phosphorus dynamics and subsequent management decisions interact with other resources, namely water, energy, other nutrients, and crops, and P dynamics at the local scale interact with global-scale events. For instance, increases in energy prices affected crop choices in 2008 (e.g., corn production for biofuels increased dramatically), and thus P dynamics. An increase in P prices was also one of the contributors to increases in input prices in agricultural production, and thus affected crop choices as well. Thus, energy prices affect P dynamics, and P prices also indirectly affected energy prices by affecting the price of alternative fuels. Cross-scalar interactions are also bidirectional: The price of P affects the efficiency of P use in Maricopa County by affecting how farmers use this input, and the consumption of mineral P in Maricopa County, although small, ultimately contributes to global increases in price. To understand what factors interact to create the urban agricultural P cycling system in Maricopa County, we must look at cross-sectoral, agricultural and nutrient commodities, and cross-scalar, local and global, relationships.

Comparison of Maricopa County agriculture P cycle and the global agricultural P cycle

Although many orders of magnitude smaller, the Maricopa County agricultural P system was consistent with the global agricultural P system in terms of inputs and uptake, but differed with regard to harvests, losses, and recycling flows of P. In Maricopa County, non-food commodities contributed to more of harvested P compared with the global scale. In this study I assumed that 100% of manure in Maricopa County was recycled, based on USGS report assumptions. According to Cordell et al. (2009) only 50 % of P in manure is recycled to agriculture globally. I cannot compare the amount of P in human excreta as a ratio to inputs of chemical fertilizer at the two scales, because the global system is a closed system by definition, while the Maricopa County system is open (Fig 17). The high proportion of excreta to chemical fertilizer in Maricopa County is because the County imports most of its food. It appears that recycling of manure and biosolids at the urban-agriculture interface of Maricopa County are proportionately larger than at the global scale. However, the effectiveness of such recycling is unclear (see discussion on uncertainty).

There are fewer losses of P to water in the Maricopa County system than in the global agricultural system. Minimal runoff in Maricopa County is due to high evaporation and the presence of few freshwater bodies, both features of an arid ecosystem. Childers et al. (2011) reviewed ranges of P fluxes in the global food system and found that P losses to waterways may be an order of magnitude higher than the estimate used by Cordell et al. (2009), making Maricopa County's limited losses of P even more distinct from most agricultural production systems of the world. Minimal loses to water bodies, and possible soil accumulation, are highly influenced by the biophysical characteristics of Maricopa County, while crop allocation and recycling flows are shaped by both the local socio-economic context and by proximity to the city, as well as by global economic pressures. These particularities must be considered when managing P.

Future management strategies

Water as a driver at the urban-agricultural system in Phoenix.

Phosphorus is an essential input to agricultural production, but is not singled out as a priority in Maricopa County. Still, P is dependent on and influences the management of other resources that are priorities in the region (e.g., nitrogen and water). In Phoenix, water management has been and will continue be an important driver in the future of agriculture. To enable continued urban development, managers favor retiring agricultural lands to free up limited water for urban uses. However, retiring agricultural lands may prove to exacerbate urban heat island effects, which is also a concern in Phoenix. The urban heat island is the phenomenon of higher temperatures, especially nighttime temperatures, in built-up areas of a city than that of surrounding rural areas. In Phoenix, nighttime temperatures are 5 degrees Celsius warmer in the city that in the desert surroundings (Baker et al., 2002). If we transform farmland to urban uses we may reduce water consumption but increase energy consumption for cooling.

Decreasing the allocation of water to agricultural use may also diminish the flexibility of municipal water allocation during periods of large inter-annual fluctuations in water supply (Bolin, Seetharam, & Pompeii, 2007). That is, in periods of drought cities may ask farmers to let their land fallow and lease their water rights to the city. If there is no water in agricultural production there is less buffer to inter-annual fluctuations as urban water-use is not flexible. Although scientists and managers have started to think about the trade-offs involved in the transition from agricultural to urban land uses (notably Gober, 2010 and Guhathakurta & Gober, 2010), nutrients have not been a major topic of discussion. Water management and urbanization will inherently have an effect on P cycling in Phoenix. I have already documented this link through the current recycling of wastewater and biosolids (also shown in Ch.2). As the Phoenix population grows, a decrease in agricultural production would result in decreased fertilizer inputs but increased imports of P as food. In addition, the conversion of agricultural land to urban uses reduces P accumulation in agricultural soils.

If we manage for P in addition to managing for water, other scenarios are possible. One scenario would be to keep agriculture as part of the urban mosaic in Phoenix from a local food security perspective (if we produce more food here), as well as in terms of national, or even a global P management perspective. Although there are trade-offs between focusing on P agricultural dynamics versus other sectors of the urban ecosystem, and between the management of P versus other resources (e.g., water), there are also a number of benefits. For example:

1. The mosaic of urban and agricultural land uses in Maricopa County presents an opportunity to tighten nutrient loops through better waste recycling and agricultural product distribution. The proximity of agricultural production, which needs P as an input, and concentrated populations, which produce high P waste, creates the added benefit of productive waste management for cities and farmers. Cities benefit because they must pay to dispose of the waste regardless of its destination, and local recycling is less expensive. It also makes it easier to conform to environmental regulations about waste management (e.g., pollutants and pathogens) because safety standards will need to be high to engender positive public perception for the reuse of human waste in Western culture. It may be easier to gain support for the large-scale recycling of food waste as compost than for human excreta (see Drangert (1998) for a discussion of the barriers and opportunities provided by public perception of human waste recycling). Recycling of high nutrient waste would significantly decreases landfill accumulation, and its attendant negative environmental consequences. Farmers may even pay cities for recyclable high-nutrient waste, reducing the financial burden of waste collection on cities. Farmers benefit because P inputs from city waste are less subject to the uncertainty and fluctuations associated with the global chemical fertilizer market. The proximity of urban and agricultural land also overcomes the significant barrier of high transportation costs to waste recycling (Magid, et al., 2002).

2. Previous studies have suggested that tightening feedback loops between food producers and consumers, which can occur with the co-location of urban and

agricultural land uses, can lead to more environmentally sound production decisions (O'Hara & Stagl, 2001 and others). If food is consumed close to where it is produced, food spoilage during transportation and storage is reduced, resulting in less high P organic material waste. And, producers can avoid over-production by responding to direct consumer demand. In addition, when local food is produced with internal sources of recycled P, i.e., recycled solid and liquid organic waste from agricultural and urban uses, agriculture becomes less dependent on external P inputs. Consequently, the price of food will fluctuate less, increasing food security (both in terms of quantity, and availability through price stability).

3. Transportation is a major cost in recycling livestock manure to croplands (Araji, Abdo, & Joyce, 2001). The co-location of feed production and animal husbandry can thus facilitate the recycling of waste by decreasing transportation distances. (See uncertainty section for a more in-depth discussion of the changes that need to be made.)

4. The limited runoff from agriculture in an arid ecosystem like Maricopa County means that P applied to agricultural fields contributes little to the eutrophication of fresh-water bodies or coastal environments, as it does in wetter areas. From a national perspective, growing crops in Arizona may minimize some eutrophication concerns associated with agricultural P management if it replaces

agriculture in eutrophication-prone areas (e.g., Mississippi River Basin), while taking advantage of a very long growing season.

5. Production at the urban-agriculture interface could decrease pressure on global P resources by decreasing P inputs from chemical fertilizer. Although this might not translate in an actual decrease of mineral-P extraction, a temporary price decrease would allow other countries to increase consumption. Lower prices would allow for a more equitable distribution of mined P to developing countries with P-deficient soils, especially in Sub-Saharan Africa, that cannot reach maximum yields with recycling alone (Weikard & Seyhan, 2008).

Some of the strategies for better P management apply to both the global agricultural system and at the urban-agriculture interface of Maricopa County, while others are dependent on local context. To improve P management in agriculture at all scales globally we should: apply P at appropriate times, apply P in the right amount (based on soil P content and the stoichiometric requirements of crops; Mikkelsen, 2004; Norton & Silvertooth, 2006), increase crop P use efficiency (Ramaekers, et al., 2010), level fields to reduce runoff, create buffer zones between fields and water sources (Beegle, et al., 2005), and separate solid and liquid waste to facilitate nutrient recycling (Drangert, 1998). Strategies that are particularly important in Maricopa County (with low precipitation, acidic calcareous soils, and a large urban area) are those that ensure P is not lost by binding to soil and sediments before reaching crops, and recycling of urban waste.

Uncertainty and need for future research

In the U.S., focus on P resources is almost exclusively associated with the management of P to minimize negative downstream environmental consequences. We can see this focus in best management practices established by the EPA and other agencies, and in the type of P-related data that are collected in the US (and the lack thereof in Maricopa County). The limited downstream eutrophication risk in Maricopa County means that very limited data are collected on P by public agencies (USGS, Agricultural Cooperative Extension, NRSC, USDA, personal communication), and this is one of the biggest contributors to the uncertainty reflected in both the average P budget for Maricopa County and the time-series analysis. Based on my interviews, P management is not a priority for farmers, other than its price (which did not fluctuate much until 2008) (Joe Sigg, AZ farm bureau; Dr. Zerkoune, NRCS; Dr. Silvertooth, U of A, personal communication). Farmers are usually more concerned about labor availability, the price of commodities, and air quality environmental regulations in Arizona (Joe Sigg, AZ farm bureau, personal communication). The scant attention given to P data collection in Maricopa County is shortsighted because without data we cannot adequately plan for how P availability at the global scale will affect local food security and economic activity. The data gap makes it difficult to understand how current P dynamics relate to other ecosystem components, and which management strategies would be most effective to decrease P needs and increase P recycling. The lack of information about P recycling is of special concern because without it we cannot make recommendations to improve recycling. The P recycling in wastewaters that does occur is unintentional, and thus the effectiveness of the recycling remains unclear. P in manure and biosolid application, although not unintentional, is not necessarily distributed evenly or according to P needs. Although we know these three P flows are recycled, we do not know how effective the recycling of wastewater, biosolids, and manure is at decreasing chemical P needs by the agricultural system.

We do not fully understand how much of recycled P is bioavailable to crops either chemically or spatially. In order to better assess the current effectiveness of wastewater, biosolid, manure, and crop residue recycling into crop production, we, as researchers, must collaborate with farmers and waste managers to collect more data. We need to conduct chemical analyses of P concentrations in irrigation water supplied with wastewater at treatment plant outflows, and along irrigation canals. These data would allow researchers to determine whether P is binding to particulates and accumulating in canal sediment before it can reach agricultural soils through irrigation. We also need access to chemical analyses of agricultural soils on a farm scale over many years in order to estimate the potential accumulation of applied P in soils (Lewis, Kaye, Gries, Kinzig, & Redman, 2006). Farmers do these analyses to determine fertilizer requirements, but not necessarily on an annual basis, and soil testing laboratories have been unable or unwilling to make farmers records available to researches. We should work with farmers directly to collect this information and communicate results back to farmers. They have a vested interest in minimizing inputs and thus costs to their farms and could benefit from better understanding how effective P recycling is.

Data collection at the farm level is also necessary to better understand the spatial distribution of recycled P flows. As discussed earlier in Chapters 2 and 3, transportation costs and emphasis on the management of resources other than P influences the distribution of recycled P flows on the landscape. Many farmers apply more fertilizer and manure than necessary because they would rather be cautious and make sure they get the highest yield possible. We know neither where nor how much over-fertilizing is occurring (Dr. Zerkoune, NRCS, personal communication). To assess if current manure recycling is an effective substitute for chemical fertilizer, we must know how it is distributed and if application matches soil and crop P needs.

A more complete and accurate assessment of the spatial distribution of P fluxes and stocks in Maricopa County would lead to better recommendations. We may need a different distribution of dairy farms and alfalfa fields, or different ways of processing manure to minimize transport costs. We should consider how future nutrient management regulations, and technological and spatial management strategies, could affect livestock producers because modern CAFOs are hot-spots of P as they accumulate excess nutrients and contribute significantly to runoff and eutrophication (Beegle, et al., 2005; Carpenter, et al., 1998; Fuhrer, 1999; Kellogg, Lander, & Moffitt, 2000).

Urban water and waste managers have both economic and environmental incentives to make waste a productive input to other sectors. Waste management practices currently recycle some but not all biosolids to agricultural production. Researchers should work with waste managers to collect data and reassess how urban organic waste is used. Perhaps more organic waste should be composted for agricultural input. There are some small-scale exchanges where landscape waste is processed by local farms, but no data are available with which to assess the effectiveness of this practice in Phoenix.

We should include fruit and vegetable, and grain production in future research (such inclusion would require collaboration with farmers as the USDA does not collect complete information on these crops and hence were not included in this study). Agricultural production in Maricopa County is currently dominated by non-food crops; however, considering the benefits of producer-consumer proximity, it would be interesting to see if increasing food production would be beneficial. This does not mean that Phoenix can, or even should, have a closed food system. Such a system would create vulnerability in urban food supply subject to fluctuating water availability, and crop production disasters. However, keeping or increasing agricultural production in the region, while acknowledging the trade-offs and complexity of the system, could be beneficial to P cycling.

Conclusions

Total harvested P from cotton and alfalfa at the Maricopa County urban-agriculture interface did not show a clear increasing or decreasing trend between 1978 and 2008, even though total acreage in agricultural production decreased and the chemical P fertilizer application rate per acre did not change. Internal cycling became tighter as alfalfa production increased to supply local dairy production, which in turn increased opportunities for manure recycling. The proximity of urban areas to agricultural areas has also permitted the recycling of wastewater and biosolids in cotton and alfalfa production. Macro-scale changes such as lending capacity and prices seemed to be responsible for the decrease in cotton production, and its replacement with alfalfa was a response to global increases in milk demand and the existing local capacity to produce dairy products. However, we need more data about production after P prices peaked in 2008 if we are to accurately gauge how the local agricultural P cycle responds to external pressures created by P scarcity (as well as other non-renewable resource costs). The Maricopa County and global agricultural systems have similar uptake and removal of P, but the allocation of P between animal feed, non-food crops, and food crops differs, as well as recycling and export P flows. Because of their proximity in Maricopa County, dairies, crop production, and cities mutually affect biogeochemical cycling (also supported by the study of N in Phoenix by Baker, et al., (2001)). Although not a completely closed loop, the dairy industry in Maricopa County does cause P recycling in this system.

Because P is a non-renewable resource that is unequally distributed around the globe, there is much uncertainty about its availability. There is a key link between food security and P security, and cities should be concerned about their resilience to fluctuations in the price and availability of food. Opportunities to close the P loop in cities include recycling P for urban and peri-urban agriculture and taking advantage of the P already stored in soils. Phoenix already recycles P, but more could be done. This chapter emphasizes the importance of both the biophysical reality of Phoenix and the economic choices that largely drive current P cycling strategies. Site-specific context (geography, space, diet, culture) must be considered when choosing technologies and recycling strategies, both for the management of P and for other resources related to food production (Blum-Evitts, 2009; Drangert, 1998). Because there has been limited data collection on P dynamics until now, especially in arid environments, researchers must work with practitioners to collect data and devise more sustainable strategies for P management.

Chapter 4

CONCLUSION

Although cities are main trade and consumption centers, the urban food system has not been highly visible. Technology has made food processing, transportation, and storage easy. Moreover, through our history of urbanization and environmental policy our legacy of a rural-agrarian society has lead us to designate agriculture and related activities as rural issues (Pothukuchi & Kaufman, 1999). In light of increasing energy costs, detrimental environmental and health effects of current agricultural practices, and a shift to systems thinking in agro-ecological research fields, the separation of cities and food systems now seems inappropriate.

This thesis has shown how management of P, an essential component in food production, is not just a rural or agricultural issue but a cross-scalar and cross-sectoral urban issue. Thus far, the management of P in urban environments has mostly been motivated by downstream pollution concerns. This narrow management goal is inadequate over the long term, especially in some cities, such as Phoenix, where biophysical characteristics imply low eutrophication risks. All cities, including Phoenix, are vulnerable to uncertainty about the supplies of critical resources (such as P) and related consumption products that use these resources as inputs (such as food and fiber). By recycling urban waste, livestock waste, and crop waste in and around cities back into agricultural production, we can decrease the vulnerability of urban populations to fluctuations in food and P availability. The proximity of agricultural and urban land uses in Phoenix may make such recycling easier. This makes it possible to close the human P cycle, because the co-location of downstream problems of waste management (urban) with upstream problems of uncertainty about the availability of cheap P (agricultural) allow for solutions that account for the coupling of upstream scarcity and downstream waste production. Following are the key findings of this thesis and my recommendations for further research based on these findings.

Key findings

- **Phoenix is a sink for P because of its biophysical characteristics and human decisions**: Phoenix imports more P than it exports, and has several large internal P flows related to food production, landscaping, and waste management. Flows related to food production have dominated the movement of P over the landscape, while the built environment and the location of humans correspond to the most concentrated stocks of P in the city. The biophysical characteristics of the arid environment (notably acidic calcareous soils, low rainfall, and few freshwater bodies) have limited losses of P from the system, translating into P accumulation and low eutrophication risk. Human decisions about waste management (e.g., landfills), water management (e.g., recycling of effluent), food purchasing, as well as landscaping and urbanization have also influenced how much P is imported, exported, recycled, and where P accumulates. The proximity of many land uses also shapes the opportunities for P recycling, especially in agricultural production.

- **Local context is important when comparing urban P dynamics with other locations and scales:** Phoenix accumulates more P than other cities for which P budgets exist. This large accumulation, as well as high throughput of subsystems, is due to the biophysical and human decisions mentioned above. Differences between the Maricopa County urban-agriculture interface and the global agricultural P budget highlight how little runoff and the co-location of P sources and needs in Phoenix permit more recycling. Even with these differences, the problems of vulnerability to fluctuations in P availability, and degradation of downstream ecosystems applies to most cities. Many cities across the globe are becoming concerned with how to recycle high P waste back into agricultural production (notably Scandinavian counties, and China (Drangert, 1998 and others). My research in Phoenix is thus timely, contributing to the understanding of how the biophysical characteristics of an arid city and past and present decisions to manage resources shapes P cycling (and recycling options).
- **Recycling of P in Phoenix is large but often unintentional:** The complete P budget of Phoenix shows large fluxes of P among subsystems, including the recycling of manure, biosolids, and wastewater. However, all three of these resources are managed with other resources than P in mind (e,g., N availability, minimize pathogens, or decrease water

scarcity). Despite this lack of focus on P, the “serendipitous” recycling of P at the Phoenix urban-agriculture interface seems to have increased between 1978 and 2008—this is largely attributable to a shift from cotton to alfalfa production. Alfalfa hay is an input to local dairy production, P in the manure from these cows is recycled to agricultural production, and the P in locally consumed milk is partially recycled through wastewater management. Interestingly, the annual amount of harvested P in cotton and alfalfa production did not change during the study period, despite a decrease in agricultural acreage and a relatively constant application of chemical P fertilizer per acre, indicating higher P recycling or more efficient use of P resources.

- **The link between P dynamics and the management of other resources affects the future of P cycling:** Current P cycling is an unintended consequence of economic and social factors that drive changes in the management of the local landscape and resources. The price of agricultural commodities and the focus of institutions on management for water scarcity in the future have strongly affected urban ecological dynamics. Current management of the urban ecosystem is based on economic, political, and social signals that, as of now, do not intentionally manage P cycling (and probably other urban ecosystem functions), and thus may not be “well tuned” for sustainably managing P.

This thesis reveals the hidden and serendipitous effects of unintended P management and underscores the need to intentionally manage P if we want to maximize the advantages of P recycling. The future of P cycling is highly dependent on how a multitude of managers, including city planners, city governments, water managers, and waste managers, which are uncoordinated, decide to focus their management of a subsection of the urban ecosystem. In fact, coordination between these managers is needed. If the focus continues to be on increased urbanization and water rights then I suggest that P dynamics will become more linear (i.e., less recycling and larger inputs and outputs). Based on the importance of food imports and recycling of P flows back to agricultural lands both in the 2005 P budget and the changes in P dynamics at the urban-agriculture interface, if urbanization increases there will be more food imports, and less agricultural land to recycle P waste. If management of agriculture continues to respond mostly to direct commodity price signals, then future P cycling may also be more linear because cotton prices are increasing while alfalfa and milk prices are decreasing; which would decrease the importance of alfalfa and dairy production recycling. A more linear flow of P through the Phoenix area may lead fluctuations in the availability of upstream resources to have more negative effects at the Phoenix scale and eventual food insecurity in the long-term. . If, on the other hand, the functioning and role of P cycling in the Phoenix Valley is explicitly recognized and made part of policy and planning decisions then the existing recycling infrastructure, the proximity of land-uses, and the low eutrophication risk could be used as an asset to create a closed-loop P cycle.

The co-management of P with other resources is needed for both local and global management: The link of P to other resources is not only internal to the Phoenix system, as shown in the points above. The price of P fertilizer (and thus its availability) is strongly linked to the price of energy. Thus, tightly cycling P at the local Phoenix scale would also decrease our vulnerability and contribution to problems associated with other globally scarce resources. Farmers, and eventually consumers, are concerned with input prices, and the price of fertilizer, energy, water, and food are related and must be thought of as such. Thus, the improved understanding of P cycling from a holistic perspective, and recommendations for increased recycling in this thesis are not only timely with respect to P availability concerns, but also with respect to the management and allocation of many scarce (and essential) resources.

- **A lack of data about urban P cycling limits our understanding of the system and how we can manage it better**: There is little publicly available data on the flow of materials, notably construction materials, because privacy rights limit government data collection and its dissemination to researchers. In addition, limited concerns about eutrophication in Maricopa County have dissuaded many regulatory agencies from allocating resources to monitor P flows in the environment. These data limitations severely restrict the conclusions and recommendations I can make about local nutrient management, especially about the current effectiveness of P recycling fluxes.

Recommendations for further research and better management

-Use participatory research methods to fill data gaps and encourage change in management strategies: Data probably exist on both the flow of P-containing materials and their distribution on the landscape, but these data are not available publically. For example, farmers likely have quantitative records of manure application, and construction companies have records on materials purchased for houses and infrastructure in the city. If we were to offer practitioners a mutually beneficial relationship via collaboration, they would be more likely to provide access to better information. Collaboration would also make it possible to collect new data. For example, where necessary information on soil and water P concentrations are not available, collaboration may facilitate access to farmland so that samples could be collected. However, such collaboration often requires continued conversations over a period of time. Such collaborations require continuity, which in turn requires institutional support for community engagement.

Based on the limited interview data I collected, P sustainability is not a priority in Maricopa County. The first steps towards sustained collaboration would be to assess how P sustainability links to current stakeholders' priorities, and educate practitioners about why P is an important resource for them.

Researchers and practitioners need a shared understanding about the role of sustainable P management in the region in order to improve P management. Unless researchers and practitioners have shared goals, access to new data and additional data collection will only increase theoretical understanding but will do nothing to enhance real-world outcomes.

I believe that one of the greatest benefits of participatory research is that it increases the likelihood that research findings will be used, and used properly. Even with increased access to data, research will still be uncertain about current and future system dynamics. When practitioners only partially understand research findings they can misuse them to support existing management goals instead of changing management for the better. With participatory research, stakeholders understand the uncertain nature of our knowledge of systems and the uncertain nature of the recommendations based on that knowledge. In addition, an open dialogue between researchers and stakeholders facilitates an iterative process through which we accommodate new knowledge and adjust management practices.

-Connect P research and management options with other resources: When managing human-dominated systems such as cities, understanding interactions between ecosystem functions and multiple resources is essential because ecosystem services operate interdependently (Bennett, Peterson, & Gordon, 2009; Millennium Ecosystem Assessment, 2005). Phosphorus management is related to many activities, including food production and waste management, and many resources, most notably water and energy, all of which are sustainability concerns. In Phoenix, the link between nutrient flows and water management is already evident and should continue to be explored. A better understanding of how P dynamics match with the other macro-nutrients, C and N, will be essential to increase our understanding of cities as ecosystems, and our ability to manage them as such.

-**Accommodating uncertainty**: In spite of wide-spread recognition that urban ecosystems are different from non-urban ones, we have not fully acknowledged the corollary fact that methods used to quantify uncertainty in non-urban ecosystems are inadequate when applied to urban ecosystems. We need to do more research on methods to manage uncertainty in urban nutrient studies. In order to better manage uncertainty, we must understand the reasons for the uncertainty, as well as the effect of uncertainty on recommendations and their usefulness. Accommodating for uncertainty that cannot be minimized via additional data collection will require the development of adaptive and iterative research and management strategies.

Framing P sustainability in larger context of urban sustainability

Phosphorus management is a wicked problem, both at local and global scales. This thesis shows how current P cycling, and the range of P-management opportunities for the future in Phoenix present wicked problem characteristics. P cycling is unique, presents cross-scalar interactions, is subject to long-term dynamics, and is affected differently by a range of stakeholders in Phoenix. Further, the strong interaction of P cycling with other resources (especially water) illustrates how solutions to the unsustainable management of one resource are neither right nor wrong because there exist trade-offs.

In *Cities as Sustainable Ecosystems* Newman & Jennings (2008) suggest designing infrastructure in cities as support systems by using technologies that "meet genuine need, [a]re optimally efficient and clean, [a]re developed by participatory science, [and] function as part of integrated systems using the lessons from nature within sustainable systems" (pg. 205). One-dimensional management of a single resource like P, N, or water, is unsustainable because resources interact with and affect one another.

P is an essential resource for life, which is both influenced by human decisions and by biophysical characteristics like climate in a city. We must consider its management in concert with other resources. Following Newman and Jennings' criteria, in order to supply food (meet genuine needs) and limit pollution (efficient and clean), we must change the way we manage P resources not only in the agricultural system but through the food system, which includes production, consumption, and disposal which are concentrated in cities. We must involve stakeholders (participatory science) to co-evolve management strategies to ensure accessibility to food for urban residents now and in the future by closing the P cycle at both the local and global scales using the lessons from nature.

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APPENDIX A

METADATA FOR CHAPTER 2: PHOSPHORUS FLUXES, STOCKS, ASSUMPTIONS, AND SPATIAL DATA

Category	P flux (Gg/yr)	P stock (Gg)	Material flux	unit	Material Stock	unit	P concentration	unit	generic calc for P	sources for P concentration	sources for material
Dry Deposition	0.195022861				NA	NA	0.195022861	Gg P	(avg dry dep * d^-1 * m^-2) * 365 d/yr * Area of CAP	CAP LTER Website	
Wet Deposition	7.44692E-05		193	mm rain/yr	NA	NA	74.46919846	Kg P	avg wet dep conc per site * avg rainfall * Area of CAP	CAP LTER Website	CAP LTER Website
Xeric Residential Soil		3.86	1607	km2	NA	NA	2.4	g/m2	P conc * land use area	Kaye et al. (2008)	2000 Landsat imagery
Mesic Residential Soil		0.82	175	km2	NA	NA	4.7	g/m2	P conc * land use area	Kaye et al. (2008)	2000 Landsat imagery
Agriculture Soil		4.29	1130	km2	NA	NA	3.8	g/m2	P conc * land use area	Kaye et al. (2008)	2000 Landsat imagery
Desert Soil		8.45	4697	km2	NA	NA	1.8	g/m2	P conc * land use area	Kaye et al. (2008)	2000 Landsat imagery
Non-Residential, Urban Soil		0.4	176	km2	NA	NA	2.3	g/m2	P conc * land use area	Kaye et al. (2008)	2000 Landsat imagery

Chemical fertilizer to agricultural soils	1.6	NA	3,006,844	kg of P in Maricopa	NA	NA	NA	NA	P for county *(ag acres in CAP/ agr acres in county)	NA	Ruddy et al. (2006)
Chemical fertilizer to urban soils	0.3		300,684	kg of P	NA	NA	NA	NA	directly from the lit.	NA	Ruddy et al. (2006)
Litterfall, trees, desert	0.072963198	NA	40.53511	Gg C / year	NA	NA	0.0009	% P by dry weight	flux of C * 2 * P conc in xeric trees and scaled to mesquite leaf	Xeric trees: Williams and da Silva (1997); Mesquite leaf: Muthaiya and Felker (1997)	McHale et al. In prep.
Litterfall, shrubs, desert	0.071507128	NA	65.00648	Gg C / year	NA	NA	0.00055	% P by dry weight	flux of C * 2 * P conc whole plan (Larrea sp. And Parthenium sp.)	Lajtha and Schlesinger (1988)	McHale et al. In prep.
Uptake, ag, tree	0.00439796	NA	1.5707	Gg C / year	NA	NA	0.0014	% P by dry weight	flux of C * C * 2 * weighted avg(40% root P conc, 40% wood P conc, 20% leaf P conc.)	Williams and Da Silva (1997)	McHale et al. In prep.
Uptake, ag, shrub	0.00131306	NA	0.3955	Gg C / year	NA	NA	0.00166	% P by dry weight	flux of C * C * 2 * weighted avg(40% root P conc, 30% wood P conc, 30% leaf P conc.)	Williams and Da Silva (1997)	McHale et al. In prep.

Uptake, ag, other veg	1.356	NA	678	Gg C / year	NA	NA	0.001	% P by dry weight	flux of C * 2 * P conc	Meyer and Brown (1985)	McHale et al. In prep.
Uptake, desert, tree	0.072963198	NA	40.53511	Gg C / year	NA	NA	0.0009	% P by dry weight	flux of C * 2 * P conc in xeric trees and scaled to mesquite leaf	Xeric trees: Williams and da Silva (1997); Mesquite leaf: Muthaiya and Felker (1997)	McHale et al. In prep.
Uptake, desert, shrub	0.071507128	NA	65.00648	Gg C / year	NA	NA	0.00055	% P by dry weight	flux of C * 2 * P conc whole plan (Larrea sp. And Parthenium sp.)	Lajtha and Schlesinger (1988)	McHale et al. In prep.
Uptake, desert, other veg	0.049089112	NA	24.54455581	Gg C / year	NA	NA	0.001	% P by dry weight	flux of C * 2 * P conc	Meyer and Brown (1985)	McHale et al. In prep.
Uptake, urban nonres, tree	0.004169088	NA	1.48896	Gg C / year	NA	NA	0.0014	% P by dry weight	flux of C * C * 2 * weighted avg(40% root P conc, 40% wood P conc, 20% leaf P conc.)	Williams and Da Silva (1997)	McHale et al. In prep.
Uptake, urban nonres, shrub	0.00087648	NA	0.264	Gg C / year	NA	NA	0.00166	% P by dry weight	flux of C * C * 2 * weighted avg(40% root P conc, 30% wood P conc, 30% leaf P conc.)	Williams and Da Silva (1997)	McHale et al. In prep.

Uptake, urban nonres, lawns	0.012204544	NA	2.77376	Gg C / year	NA	NA	0.0022	% P by dry weight	flux of C * 2 * P conc	Williams and Da Silva 1997	McHale et al. In prep.
Uptake, urban nonres, other veg	0.00081533	NA	0.407665116	Gg C / year	NA	NA	0.001	% P by dry weight	flux of C * 2 * P conc	Meyer and Brown (1985)	McHale et al. In prep.
Uptake, urban residential mesic, tree	0.0111622	NA	3.9865	Gg C / year	NA	NA	0.0014	% P by dry weight	flux of C * C * 2 * weighted avg(40% root P conc, 40% wood P conc, 20% leaf P conc.)	Williams and Da Silva (1997)	McHale et al. In prep.
Uptake, urban residential mesic, shrub	0.00099932	NA	0.301	Gg C / year	NA	NA	0.00166	% P by dry weight	flux of C * C * 2 * weighted avg(40% root P conc, 30% wood P conc, 30% leaf P conc.)	Williams and Da Silva (1997)	McHale et al. In prep.
Uptake, urban residential mesic, lawns	0.0217756	NA	4.949	Gg C / year	NA	NA	0.0022	% P by dry weight	flux of C * 2 * P conc	Williams and Da Silva 1997	McHale et al. In prep.
Uptake, urban residential mesic, other veg	0.001994186	NA	0.997093023	Gg C / year	NA	NA	0.001	% P by dry weight	flux of C * 2 * P conc	Meyer and Brown (1985)	McHale et al. In prep.

Uptake, urban residential xeric, tree	0.052327134	NA	29.07063	Gg C / year	NA	NA	0.0009	% P by dry weight	flux of C * 2 * P conc in xeric trees and scaled to mesquite leaf	Xeric trees: Williams and da Silva (1997); Mesquite leaf: Muthaiya and Felker (1997)	McHale et al. In prep.
Uptake, urban residential xeric, shrub	0.001803054	NA	1.63914	Gg C / year	NA	NA	0.00055	% P by dry weight	flux of C * 2 * P conc whole plan (Larrea sp. And Parthenium sp.)	Lajtha and Schlesinger (1988)	McHale et al. In prep.
Uptake, urban residential xeric, other veg	0.014283614	NA	7.141806977	Gg C / year	NA	NA	0.001	% P by dry weight	flux of C * 2 * P conc	Meyer and Brown (1985)	McHale et al. In prep.
Desert Trees	NA	1.614913146	NA	NA	897.17397	Gg C	0.0009	% P by dry weight	stock of C * 2 * P conc in xeric trees and scaled to mesquite leaf	Xeric trees: Williams and da Silva (1997); Mesquite leaf: Muthaiya and Felker (1997)	McHale et al. In prep.
Desert Shrubs	NA	2.5626832	NA	NA	2329.712	Gg C	0.00055	% P by dry weight	stock of C * 2 * P conc whole plan (Larrea sp. And Parthenium sp.)	Lajtha and Schlesinger (1988)	McHale et al. In prep.
Agriculture, trees	NA	0.05090876	NA	NA	18.1817	Gg C	0.0014	% P by dry weight	Stock of C * 2 * weighted avg(40% root P conc, 30% woo P conc, 30% leaf P conc.)	Williams and Da Silva (1997)	McHale et al. In prep.

Agriculture shrubs	NA	0.022734696	NA	NA	6.8478	Gg C	0.00166	% P by dry weight	Stock of C * 2 * weighted avg(40% root P conc, 30% woo P conc, 30% leaf P conc.)	Williams and Da Silva (1997)	McHale et al. In prep.
Urban non residential, trees	NA	0.131030592	NA	NA	46.79664	Gg C	0.0014	% P by dry weight	Stock of C * 2 * weighted avg(40% root P conc, 30% woo P conc, 30% leaf P conc.)	Williams and Da Silva (1997)	McHale et al. In prep.
Urban non residential, shrubs	NA	0.020784262	NA	NA	6.26032	Gg C	0.00166	% P by dry weight	Stock of C * 2 * weighted avg(40% root P conc, 30% woo P conc, 30% leaf P conc.)	Williams and Da Silva (1997)	McHale et al. In prep.
Urban residential mesic, trees	NA	0.4373446	NA	NA	156.1945	Gg C	0.0014	% P by dry weight	Stock of C * 2 * weighted avg(40% root P conc, 30% woo P conc, 30% leaf P conc.)	Williams and Da Silva (1997)	McHale et al. In prep.
Urban residential mesic, shrubs	NA	0.01776117	NA	NA	5.34975	Gg C	0.00166	% P by dry weight	Stock of C * 2 * weighted avg(40% root P conc, 30% woo P conc, 30% leaf P conc.)	Williams and Da Silva (1997)	McHale et al. In prep.

Urban residential xeric, trees	NA	1.90350435 6	NA	NA	1057.5 0242	Gg C	0.000 9	% P by dry weight	Stock of C * 2 * P conc in xeric trees and scaled to mesquite leaf	Xeric trees: Williams and da Silva (1997); Mesquite leaf: Muthaiya and Felker (1997)	McHale et al. In prep.
Urban residential xeric, shrubs	NA	0.06093261 9	NA	NA	55.393 29	Gg C	0.000 55	% P by dry weight	stock of C * 2 * P conc whole plan (Larrea sp. And Parthenium sp.)	Lajtha and Schlesinger (1988)	McHale et al. In prep.
export crop	0.305201 741	NA	NA	NA	NA	NA	0.81	lbs/acre	Number of 90*90m pixels under cotton production*conversion acres/pixel*P removal lbs/acre (at that yield)*conversion Gg/lb	USDA-NRCS (2000)	NASS 2010 crop GIS layer and USDA NASS records, personal communication
Animal feed crop	1.74	NA	NA	NA	NA	NA	1.44,1.86,0.84	lbs/acre for corn, alfalfa, other hay	Add for each crop - Number of 90*90m pixels under x crop production*conversion acres/pixel*P removal lbs/acre (at that yield)*conversion Gg/lb	USDA-NRCS (2000)	NASS 2010 crop GIS layer and USDA NASS records, personal communication

Human consumption crop	0.1	NA	see spatial data	see spatial data	NA	NA	24, 0.0037, 0.0051,0.041,1.01, 0.55, 0.73,	lbs/acre for watermelons, citrus (using grapefruit), oranges, greens, lettuce, wheat, shorghum, barley	Add for each crop - Number of 90*90m pixels under x crop production*conversion acres/pixel*P removal lbs/acre (at that yield)*conversion Gg/lb	USDA-NRCS (2000)	NASS 2010 crop GIS layer and USDA NASS records, personal communication
Surface water inputs - Salt River	0.010154461	NA	3.54914E+11	L / year	NA	NA	0.028611018	mg P / L	Baket et al. (2001) and USGS	USGS	USGS
Surface water inputs - Verde River	0.012505242	NA	2.4205E+11	L / year	NA	NA	0.051663985	mg P / L	Baket et al. (2001) and USGS	USGS	USGS

Surface water inputs - CAP Canal (Colorado R)	0.033402688	NA	8.35067E+11	L / year	NA	NA	0.04	mg P / L	Mean P conc for CAP * avg annual withdrawals from CAP canal to Maricopa County	CAP LTER	MAG (2002)
Surface water outputs - Gila River	0.112731597	NA	1.28604E+11	L / year	NA	NA	0.876579029	mg P / L	USGS and Baker et al. (2001)	USGS	USGS
CAP to urban uses	0.013666979	NA	3.41674E+11	L / year	NA	NA	0.04	mg P / L	Water flux * P conc.	CAP LTER	MAG (2002)
CAP to subsurface (underground storage or gw recharge)	0.019735709	NA	4.93393E+11	L / year	NA	NA	0.04	mg P / L	Water flux * P conc.	CAP LTER	MAG (2002)
Surface water to Irrigation	0.010847422	NA	2.85772E+11	L / year	NA	NA	0.03795825	mg P / L	Water flux *(avg P conc= (avg.salt annual load +avg. verde annual load)/(avg. salt discharge + avg. verde discharge)))	USGS	Kenny et al. (2008)
Surface water --> public supply	0.029394318	NA	7.74385E+11	L / year	NA	NA	0.03795825	mg P / L	Water flux *(avg P conc= (avg.salt annual load +avg. verde annual load)/(avg. salt discharge + avg. verde discharge)))	USGS	Kenny et al. (2008)

drinking water to irrigation	0.006419 892	NA	6.41989 E+11	L / year	NA	NA	0.01	mg P / L	Water flux * P conc.	Tempe Water Quality Lab, personal communication.	Kenny et al. (2008)
GW to Public supply	0.007434 566	NA	3.09774 E+11	L / year	NA	NA	0.024	mg P / L	Water flux * Median P conc.	AzDEQ monitoring for Phoenix Active Management Area. Personal communication.	Kenny et al. (2008)
GW to domestic (self supply)	0.000213 147	NA	8881107 000	L / year	NA	NA	0.024	mg P / L	Water flux * Median P conc.	AzDEQ monitoring for Phoenix Active Management Area. Personal communication.	Kenny et al. (2008)
Total GW withdrawals	0.039261 393	NA	1.63589 E+12	L / year	NA	NA	0.024	mg P / L	Water flux * Median P conc.	AzDEQ monitoring for Phoenix Active Management Area. Personal communication.	Kenny et al. (2008)
GW to industrial	0.000182 934	NA	7622258 500	L / year	NA	NA	0.024	mg P / L	Water flux * Median P conc.	AzDEQ monitoring for Phoenix Active Management Area. Personal communication.	Kenny et al. (2008)

GW to Irrigation	0.030803331	NA	1.28347E+12	L / year	NA	NA	0.024	mg P / L	Water flux * Median P conc.	AzDEQ monitoring for Phoenix Active Management Area. Personal communication.	Kenny et al. (2008)
waste water effluent --> Gila river	0.599779104	NA	1.54982E+11	L / year	NA	NA	3.87	mg P / L	Water flux * P conc.	CAP LTER	Lauver et al. (2000)
waste water effluent --> irrigation (agriculture and golf courses)	0.921089338	NA	2.38008E+11	L / year	NA	NA	3.87	mg P / L	Water flux * P conc.	CAP LTER	Lauver et al. (2000)
waste water effluent --> GW recharge	0.085682729	NA	22140240080	L / year	NA	NA	3.87	mg P / L	Water flux * P conc.	CAP LTER	Lauver et al. (2000)
waste water effluent --> Palo Verde powerplant (cooling)	0.535517057	NA	1.38377E+11	L / year	NA	NA	3.87	mg P / L	Water flux * P conc.	CAP LTER	Lauver et al. (2000)
Runoff from urban	0.041882363	NA	31706222400	L / year	NA	NA	1.320950887	mg P / L	see Fossum 2001 for regression equations based on land use	Fossumet al.(2001)	Fossumet al. (2001)
runoff from desert	0.003680982	NA	?	L / year	NA	NA	0.051663985	mg P / L	Kg P / ha of desert * area of desert in CAP	USGS	Estimated from USGS NWIS data for Verde River.

Biosolids	1.6773282	NA	55910.94	dry tons of biosolid produced in Maricopa per year	NA	NA	3	%	Biosolid produced/year*P conc	ADEQ (2006)	ADEQ (2006)
Asphalt	NA	7.86	NA	NA	17272	Gg	0.16	% PPA in Asphalt by weight	area of asphalt * depth *density* % of PPA*% of P in PPA	Golden et al. (2009)	Stefinov et al. 2005 and http://www.simetric.co.uk/si_materials.htm
Paper and Cardboard import	0.231839873	NA	297.05	kg paper/ per day per person	NA	NA	0.024	%	import kg per capita per day* number to days a year*pop of CAP* P conc* conversion Gg/kg	Antikainen et al. (2004)	World Resources Institute (2007)
Textiles	0.906743032	NA	0.07	lbs/ per person per day	NA	NA	2.3	%	Waste produced lbs/per capita per day* number of days a year* pop of CAP* conversion Gg/lbs* % of textiles in waste* P conc	Yang & Yang (2005)	MAG. (2005)

Paper to landfills	1.137371111		0.88	lbs/ per person per day	0.024	%	Waste produced lbs/per capita per day* number of days a year* population of CAP* conversion Gg/lbs* % of waste that is paper* P conc	Antikainen et al. (2004)	MAG. (2005)
Paper and Cardboard to recycling	0.379773923		743	tons/day	0.024	%	Recycling produced ton/ per day* number of days a year* conversion Gg/tons* % of recycling that is (paper+newspaper+cardboard+woodwaste)* P conc	Antikainen et al. (2004)	MAG. (2005)
Humans		3.2386			1	%	(popl size * (avg human weight >18 * % popl >18* P conc.)+(avg human weight <18 * % popl <18*P conc))	Harper et al. (1977)	U.S. Census Bureau (2000);Avg Size of US popl by distr: CDC-NCHS
Humans Net of Immigration & Emigration	0.10004				1	%	Human_P_stock * %_change_in_stock_size	Harper et al. (1977)	Popl change: U.S. Census Bureau (2009); Avg Size of US popl by distr: CDC-NCHS

Dog Food Consumed	0.56267		113.9013	19.5	kg food/animal/yr	0.5	%	Dog Population in CAP * Dog Food requirement kg/dog per yr * %P in food	AAFCO; Personal communication Baker; U.S. Census Bureau (2009) %P: (Harper et al. (1977)	AAFCO
Dogs		0.0988				1	%	# of dog (proportional to humans) * %P in dogs	Harper et al. (1977)	Personal Communication Baker; human pop: U.S. Census Bureau (2009)
Dogs Net of Immigration & Emigration	0.0024					1	%	change in dog popl from 2000-2009 * % P in dogs	Harper et al. (1977)	Personal communication Baker; U.S. Census Bureau (2009)
Dog Poop	0.5507					1.425	kg/yr /Dog	# dogs (proportional to human pop)*P pre dog	Baker et al. (2007)	
Cat Food Consumed	0.137081247		41.4186535	2.99	kg food/animal/yr			Cat Population in CAP * Cat Food requirement kg/cat per yr * %P in food	AAFCO	AAFCO
Cats		0.02				1	%	change in cat popl from 2000-2009 * % P in cats	Harper et al. (1977)	Perconal communication Baker;human popl: U.S. Census Bureau (2009)

Cat Poop	0.1688						1.425	kg/yr /cat	#cat (proportional to human pop)*P pre dog	Baker et al. (2007)	
Cow Feed	1.535161675		29471.7259	kg/animal/yr			0.12	%P	Cow Population in CAP * Cow Feed requirements * %P in feed	Hall et al. (2009)	# cows: USDA (2007)
Cows		1.87	185322.5	cows					# cows * avg weight * %P	Harper et al. (1977)	# cows: USDA (2007), % cow in co. that is beef vs dairy: AASS & U of A (2005), avg weight of cows beef & dairy: ASAE. (2004).
Cow Manure	1.037806		185322.5	cows			5.6	(gP /g animal/yr)	P in manure * Popl of cows	Gilbertson et al. (1979)	# cows: USDA (2007), % cow in co. that is beef vs dairy: AASS & U of A (2005), avg weight of cows beef & dairy: ASAE. (2004).
Cow Milk	0.341763306		9131.2500	kg milk/animal/yr	0.5722	% of CAP cows that are dairy cows	0.0004	g P/g milk	Dairy cow popl * Milk produced per dairy cow * Amount of P in milk	Bender & Bender (1999) and Gilbertson et al. (1979)	# cows: USDA (2007), % cow in co. that is beef vs dairy: AASS & U of A (2005), Gilbertson et al. (1979)

Milk export from CAP	0.14		see assumptions

Assumptions and Notes for the calculation of stocks and flows.

Category	Assumptions	Notes
Dry Deposition		Specificity: 2005 from 4 locations (LDS, ORG, PSS, PVR), downloaded: data from CAP website on 15 May 2010
Wet Deposition		Specificity: 2005 from 3 locations (LDS, PSS, PVR), Downloaded: downloaded data from CAP website on 15 May 2010
Xeric Residential Soil	0 - 30cm avg soil conc by land use	These calculations are following the "traditional modeling approach" discussed in Kaye et al 2008
Mesic Residential Soil	0- 30cm avg soil conc by land use	These calculations are following the "traditional modeling approach" discussed in Kaye et al 2008
Agriculture Soil	0 - 30cm avg soil conc by land use	These calculations are following the "traditional modeling approach" discussed in Kaye et al 2008
Desert Soil	0 - 30cm avg soil conc by land use	These calculations are following the "traditional modeling approach" discussed in Kaye et al 2008
Non-Residential, Urban Soil	0- 30cm avg soil conc by land use	These calculations are following the "traditional modeling approach" discussed in Kaye et al 2008
Chemical fertilizer to agricultural soils	equally applied to ag. fields	53% of agricluture in Maricopa County is in CAP based in USDA field office data average 2002 and 2007 and the NASS crop layer data (see spatial section)
Chemical fertilizer to urban soils	equally applied to mesic soils	
Litterfall, trees, desert	desert veg. is steady state over 1 yr and set litterfall equal to uptake	
Litterfall, shrubs, desert	desert veg. is steady state over 1 yr and set litterfall equal to uptake	

Uptake, ag, tree	We set uptake = net primary productivity and assume C:P of uptake is same as mean P content for each plant type. Our NPP data are in Gg C; we convert these to dry weight assuming biomass is 50% C by dry weight.	
Uptake, ag, shrub	We set uptake = net primary productivity and assume C:P of uptake is same as mean P content for each plant type. Our NPP data are in Gg C; we convert these to dry weight assuming biomass is 50% C by dry weight.	
Uptake, ag, other veg	We set uptake = net primary productivity and assume C:P of uptake is same as mean P content for each plant type. Our NPP data are in Gg C; we convert these to dry weight assuming biomass is 50% C by dry weight.	
Uptake, desert, tree	We set uptake = net primary productivity and assume C:P of uptake is same as mean P content for each plant type. Our NPP data are in Gg C; we convert these to dry weight assuming biomass is 50% C by dry weight.	
Uptake, desert, shrub	We set uptake = net primary productivity and assume C:P of uptake is same as mean P content for each plant type. Our NPP data are in Gg C; we convert these to dry weight assuming biomass is 50% C by dry weight.	
Uptake, desert, other veg	We set uptake = net primary productivity and assume C:P of uptake is same as mean P content for each plant type. Our NPP data are in Gg C; we convert these to dry weight assuming biomass is 50% C by dry weight.	Assume cactus Prickly Pear value
Uptake, urban nonres, tree	We set uptake = net primary productivity and assume C:P of uptake is same as mean P content for each plant type. Our NPP data are in Gg C; we convert these to dry weight assuming biomass is 50% C by dry weight.	
Uptake, urban nonres, shrub	We set uptake = net primary productivity and assume C:P of uptake is same as mean P content for each plant type. Our NPP data are in Gg C; we convert these to dry weight assuming biomass is 50% C by dry weight.	

Uptake, urban nonres, lawns	We set uptake = net primary productivity and assume C:P of uptake is same as mean P content for each plant type. Our NPP data are in Gg C; we convert these to dry weight assuming biomass is 50% C by dry weight.	
Uptake, urban nonres, other veg	We set uptake = net primary productivity and assume C:P of uptake is same as mean P content for each plant type. Our NPP data are in Gg C; we convert these to dry weight assuming biomass is 50% C by dry weight.	Assume cactus Prickly Pear value
Uptake, urban residential mesic, tree	We set uptake = net primary productivity and assume C:P of uptake is same as mean P content for each plant type. Our NPP data are in Gg C; we convert these to dry weight assuming biomass is 50% C by dry weight.	
Uptake, urban residential mesic, shrub	We set uptake = net primary productivity and assume C:P of uptake is same as mean P content for each plant type. Our NPP data are in Gg C; we convert these to dry weight assuming biomass is 50% C by dry weight.	
Uptake, urban residential mesic, lawns	We set uptake = net primary productivity and assume C:P of uptake is same as mean P content for each plant type. Our NPP data are in Gg C; we convert these to dry weight assuming biomass is 50% C by dry weight.	
Uptake, urban residential mesic, other veg	We set uptake = net primary productivity and assume C:P of uptake is same as mean P content for each plant type. Our NPP data are in Gg C; we convert these to dry weight assuming biomass is 50% C by dry weight.	Assume cactus Prickly Pear value
Uptake, urban residential xeric, tree	We set uptake = net primary productivity and assume C:P of uptake is same as mean P content for each plant type. Our NPP data are in Gg C; we convert these to dry weight assuming biomass is 50% C by dry weight.	
Uptake, urban residential xeric, shrub	We set uptake = net primary productivity and assume C:P of uptake is same as mean P content for each plant type. Our NPP data are in Gg C; we convert these to dry weight assuming biomass is 50% C by dry weight.	

Uptake, urban residential xeric, other veg	We set uptake = net primary productivity and assume C:P of uptake is same as mean P content for each plant type. Our NPP data are in Gg C; we convert these to dry weight assuming biomass is 50% C by dry weight.	Assume cactus Prickly Pear value
Desert Trees		
Desert Shrubs		
Agriculture, trees		
Agriculture shrubs		
Urban non residential, trees		
Urban non residential, shrubs		
Urban residential mesic, trees		
Urban residential mesic, shrubs		
Urban residential xeric, trees		
Urban residential xeric, shrubs		
export crop		
Animal feed crop		

Human consumption crop	Ten % of food produced here is assumed to spoil before it can reach human food supply based on Pimentel, D., W. Dritschilo, J. Krummel, and J. Kutzman. 1975. Energy and land constraints in food protein production. Science;(United States) 190.
Surface water inputs - Salt River	Mean annual load 1999-2004 (range 0.01-8.1 mg/L orthophosphate unflfiltered)
Surface water inputs - Verde River	Mean annual load 1999-2004 (range 0.01-7.3 mg P/L unfiltered)
Surface water inputs - CAP Canal (Colorado R)	Mean annual load 1998-2004 (range 0.00-0.81 mg P/L)
Surface water outputs - Gila River	Calculated using USGS PO4 and discharge data, extrapolated chemistry data across discharge using method described in Baker et al 2001, summed loads for each year, and averaged annual loads across 1999 - 2004.Mean annual load 1999-2004 (range 0.01-9.4 mg P/L unfiltered)
CAP to urban uses	CAP canal data 1998-2004
CAP to subsurface (underground storage or gw recharge)	
Surface water to Irrigation	P concentration were calculated using annual loads and dischare from the Salt and Verde Rivers averaged over 1999-2004. year used: 2005
Surface water --> public supply	
drinking water to irrigation	years used:1998 and 2005, P concentrations are <0.02 mg P / L (below detection limit).

GW to Public supply		year used: 2005
GW to domestic (self supply)		year used: 2005
Total GW withdrawals		year used: 2005
GW to industrial		year used: 2005
GW to Irrigation		year used: 2005
waste water effluent --> Gila river	Calculated as 28% of waste water treatment plant effluent production	Concentration is average total P value from 91st Ave treatment plant from 1998 - 2004. (range in 1997 0.72-29.37 mg/L)
waste water effluent --> irrigation (agriculture and golf courses)	Calculated as 43% of waste water treatment plant effluent production	Concentration is average total P value from 91st Ave treatment plant from 1998 - 2004. (range in 1997 0.72-29.37 mg/L)
waste water effluent --> GW recharge	Calculated as 4% of waste water treatment plant effluent production	Concentration is average total P value from 91st Ave treatment plant from 1998 - 2004. (range in 1997 0.72-29.37 mg/L)
waste water effluent --> Palo Verde powerplant (cooling)	Calculated as 25% of waste water treatment plant effluent production.	Concentration basted on 91st Ave WWTP 1998-2004.
Runoff from urban		Note that this is the sum of annual runoff and TP loads for 12 of the Phoenix metro cities. Regression equations are presented in Fossum 2001 and can be used with current CAP land use data to get a better estimate. Also note that these estimates are from small urban catchments and do not take into account stormwater infrastructure (ret basins, etc), and therefore are probably a big overestimate.

runoff from desert		
Biosolids		
Asphalt		
Paper and Cardboard import		
Textiles		
Paper to landfills		
Paper and Cardboard to recycling		
Humans		Data is for humans <18 years of age and humans >18 years of age (online tool year: 2009)
Humans Net of Immigration & Emigration	Linearity of data from 2000-2010	Averaged over from 2000-2010
Dog Food Consumed	see the note	Dog Food Requirements for a 19.5 kg dog. Low Estimate based on P requirement and not what they are actually consuming
Dogs	%P for dog is same as humans	Baker doesn't cite how he calc the ratio of # of dogs in CAP. This is based on the change in popl from 2000-2009.
Dogs Net of Immigration & Emigration		Avg from 2000-2010
Dog Poop		Baker et al 2007 Household Flux Calculator - dog food consumption is equal to dog excretion. Table 3 gives intake of P in kg/yr for dogs of several weights. The number listed here (1.425) is an average P (kg/yr) for 10, 20, 30 and 40 kg dogs (P = 0.5, 1.2, 1.7, 1.7 and 2.3). Note the units are kg/yr/dog and consumption of dog food = excretion by dog
Cat Food Consumed		Cat Food Requirements for a 2.99 kg cat. Low Estimate based on P requirement and not what they are actually consuming

Cats	%P for cat is same as humans	
Cat Poop	assume it's the same as dog numbers	
Cow Feed		Cow Feed Requirements for a 1007.6667 kg Cow. Low Estimate based on P requirements and not what they are actually consuming
Cows	%P for dog is same as humans	Number of cows is an average in Maricopa County from 2002 & 2007
Cow Manure	%P for dog is same as humans	Number of cows is an average in Maricopa County from 2002 & 2007. This manure number is consistent with the cow to total manure production in the county extrapolated from 1997 USDS data
Cow Milk		40% of milk produced in the area is exported based on United Darymen Association of Arizona (2010) personal communication
Milk export from CAP	40 % of milk is exported. Based on personal communication with United Dairymen of Arizona saying 2/3 is exported but we also import a large amount.	

Spatial data.

Category	Area	unit	Spatial Layer	Source	Generic calc for P	Assumptions and Notes	P stock (Gg/m^2)
Mesic soil	47018	90m Pixels	Mesic Residential class from 2005 Land Cover data	Buyantuyev (2007)	Stock = P(stock)/pixel# , Input = P(input)/pixel#, Output = P(output)/pixel#	Mesic soil and vegetation were calculated from the mesic residential land cover in the 2005 CAP-LTER land cover dataset. Assumed equal distribution by dividing across land class area (in pixels)	2.10059E-09

Mesic vegetation	47018	90m Pixels	Mesic Residential class from 2005 Land Cover data	Buyantuyev (2007)	Stock = P(stock)/pixel# , Input = P(input)/pixel#, Output = P(output)/pixel#	Mesic soil and vegetation were calculated from the mesic residential land cover in the 2005 CAP-LTER land cover dataset. Assumed equal distribution by dividing across land class area (in pixels)	1.20784E-09
Xeric soil	95386	90m Pixels	Xeric Residential class from 2005 Land Cover data	Buyantuyev (2007)	Stock = P(stock)/pixel# , Input = P(input)/pixel#, Output = P(output)/pixel#	Xeric soil and vegetation was based on the Xeric residential land cover class. Assumed equal distribution by dividing across land class area (in pixels)	5.04772E-09
Xeric vegetation	95386	90m Pixels	Xeric Residential class from 2005 Land Cover data	Buyantuyev (2007)	Stock = P(stock)/pixel# , Input = P(input)/pixel#, Output = P(output)/pixel#	Xeric soil and vegetation was based on the Xeric residential land cover class. Assumed equal distribution by dividing across land class area (in pixels)	2.53680E-09
Desert soil	3607694	90m Pixels	Compacted soil land cover clas from 2005 Land Cover data; Desert land use from 2000 land Use data	Buyantuyev (2007); Redman et al. (2005)	Stock = P(stock)/pixel# , Input = P(input)/pixel#, Output = P(output)/pixel#	The desert land use class and compacted soil land cover class was used to create the spatial component for desert soil. Assumed equal distribution by dividing across land class area (in pixels)	3.03387E-09
Desert vegetation	88109	90m Pixels	Vegetation land cover class from 2005 Land Cover data; Desert land use from 2000	Buyantuyev (2007); Redman et al. (2005)	Stock = P(stock)/pixel# , Input = P(input)/pixel#, Output = P(output)/pixel#	Desert vegetation was calculated from the desert land use class and vegetation land cover class. Assumed equal distribution by dividing across land class area (in pixels)	5.85694E-09

			Land Use data				
Agriculture vegetation (stock)	884	90m Pixels	Only dairy from CAP-LTER study area	USDA 2010 NASS Agricultural data	Stock = P(stock)/pixel# , No input or output	Assumed equal distribution by dividing across land class area (in pixels) of crops with woddy materials (tree (e.g., organges) and shrub crops(e.g., olives))	9.77599E-09
Urban non-residential vegetation	94879	90m Pixels	Vegetation land cover class from2005 Land Cover data; Urban land use from 2000 Land use data	Buyantuyev (2007); Redman et al. (2005)	Stock = P(stock)/pixel# , Input = P(input)/pixel#, Output = P(output)/pixel#	Urban non-residential soil was based on the intersection of urban land use data and the vegetation land cover class. Assumed equal distribution by dividing across land class area (in pixels)	1.82168E-10
Urban soil	94879	90m Pixels	Undisturbed and Compacted soil land cover class from 2005 Land Cover data; urban land use from 2000 land Use data	Buyantuyev (2007); Redman et al. (2005)	Stock = P(stock)/pixel# , Input = P(input)/pixel#, Output = P(output)/pixel#	Urban non-residential soil was based on the intersection of urban land use data and the vegetation land cover class. Assumed equal distribution by dividing across land class area (in pixels)	5.20481E-10

Agricultural soil	86095	90m Pixels	Cultivated vegetation land cover class and Compacted soil (Prior Ag use) land cover class from 2005 Land Cover data	2005 Land Cover data (Buyantuyev 2007)	Stock = P(stock)/pixel# , No input or output	The agricultural soil was derived from the CAP-LTER land cover map by combining the cultivated vegetation class and the compacted soil (prior agriculture) class. Assumed equal distribution by dividing across land class area (in pixels)	5.59244E-09
People	788771	90m Pixels	Area of CAP-LTER - Not uniformaly distributed, based on population per tract per pixel	2000 Census Tract data for Arizona	Stock = P(stock)/pixel# , Input = P(input)/pixel#, Output = P(output)/pixel#	For humans, The phosphorus stock, output, and input numbers were first calculated on a per capita basis and then divided across the number of 90 m^2 pixels for each census tract in the study area.	variable
Pets	788771	90m Pixels	Area of CAP-LTER - Not uniformaly distributed, based on population per tract per pixel	2000 Census Tract data for Arizona	Stock = P(stock)/pixel# , Input = P(input)/pixel#, Output = P(output)/pixel#	For pets, the P stock, output, and input was calculated on a per household basis and then divided similarly across 90 m pixels for each census tract area.	variable
Atmosphere, gasoline emissions and natural deposition	788771	90m Pixels	The entire CAP-LTER study area	CAP-LTER study boundary	Input = P(input)/pixel#, no stock or output	Assumed equal distribution by dividing across land class area (in pixels)	No stock

Dairy	8405	90m Pixels	Only dairy from CAP-LTER study area	Geocoded dairy farm data for Maricopa County	Stock = P(stock)/pixel# , Input = P(input)/pixel#, Output = P(output)/pixel#	Dairy was derived from geocoding publicly available dairy farms and assuming an equal number of cows (2079) and an equal amount of pixels per farm. Assumed equal distribution by dividing across land class area (in pixels)	2.79081E-08
Agriculture vegetation	55078	90m Pixels	Only agriculture from CAP-LTER study area	USDA 2010 NASS Agricultural data	Input = P(input)/pixel#, Output = P(output)/pixel#, no stock	Agriculture input and output was calculated from the those pixels that are identified to be cultivated within the CAP-LTER study area	?????
Asphalt	36822	90m Pixels	Disturbed (asphalt) land cover class from 2005 Land Cover data	Buyantuyev (2007)	Stock = P(stock)/pixel# , No input or output	The asphalt land class was based on the disturbed (asphalt) land cover class. Assumed equal distribution by dividing across land class area (in pixels)	2.43230E-08

Stock	Stock = Impervious + Desert Vegetation + Mesic Vegetation + Xeric Vegetation + Urban Non-residential Soil + Agricultural Trees + Urban Non-residential Soil + Desert Soil + Mesic Soil + Xeric Soil + Agricultural Soil + Dairy + People + Pets	Calculated by adding all rasters listed using the 'Plus' function in ArcGIS 9.3. Smoothed using a 5 cell (pixel) mean focal statistics function in ArcGIS
Input	Input = Desert Vegetation + Mesic Vegetation + Xeric Vegetation + Urban Non-residential Veg + Agricultural Trees + Dairy + People + Pets + Atmosphere + Agriculture	Calculated by adding all rasters listed using the 'Plus' function in ArcGIS 9.3.

Output	Output = Desert Vegetation + Mesic Vegetation + Xeric Vegetation + Urban Non-residential Veg + Agricultural Trees + Dairy + People + Pets + Agriculture	Calculated by adding all rasters listed using the 'Plus' function in ArcGIS 9.3.
Throughput	Input + Output	Calculated by adding the input raster and output raster with the ArcGIS 9.3 'Plus' function. Smoothed with a 5 cell radial filter in focal statistics (mean)
Accumulation	Input - Output	Calculated by subtracting the output from the input raster with the ArcGIS 9.3 'Plus' function. Smoothed with a 5 cell radial filter in focal statistics (mean)

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APPENDIX B

UNIVERSITY HUMAN SUBJECT INTERNAL REVIEW BOARD

APPROVAL, SURVEY, AND INTERVIEW PROTOCOLS

IRB approval

ASU Knowledge Enterprise Development

Office of Research Integrity and Assurance

To:	Rimjhim Aggarwal TMPCT
From:	Mark Roosa, Chair Soc Beh IRB
Date:	12/02/2010
Committee Action:	**Exemption Granted**
IRB Action Date:	12/02/2010
IRB Protocol #:	1011005756
Study Title:	Change in Phosporus Use in Maricopa County Alfalfa and Cotton Production Over Time

The above-referenced protocol is considered exempt after review by the Institutional Review Board pursuant to Federal regulations, 45 CFR Part 46.101(b)(2) .

This part of the federal regulations requires that the information be recorded by investigators in such a manner that subjects cannot be identified, directly or through identifiers linked to the subjects. It is necessary that the information obtained not be such that if disclosed outside the research, it could reasonably place the subjects at risk of criminal or civil liability, or be damaging to the subjects' financial standing, employability, or reputation.

You should retain a copy of this letter for your records.

Information Letter for Interviews and Surveys Non-Anonymous

CHANGES IN PHOSPHORUS MANAGEMENT IN ALFALFA AND COTTON PRODUCTION IN MARICOPA COUNTY

Date

Dear Participant:

I am a graduate student under the direction of Professor Rimjhim Aggarwal in the School of Sustainability at Arizona State University. I am conducting a research study to explore the practices that affect the element phosphorus's flow in the agricultural system of Maricopa County.

I am inviting your participation, which will involve a 30-60 minute interview or an email survey. The interview will be carried out in order to determine your unique perspective of (1) How have P flows in alfalfa- and cotton-production subsystems changed from 1978 to 2008? (2) What are the major determinants of changes in the urban-agricultural P subsystem? (3) How might we increase the recycling and sustainable management of P resources in the urban agricultural environment? Responses to the interview questions will be anonymous, and you as a participant will have the right to skip over questions or stop the interview or survey at any time.

Your participation in this study is voluntary. If you choose not to participate or to withdraw from the study at any time, there will be no penalty. You must be 18 or older to participate in the study.

The main benefits of your participation in the research will be your contribution to the increased understanding how phosphorus, an essential element for plant growth, flows and stock in the region have changed and how they may change in the future.

If you wish, you may choose attend a presentation of the results of this research project, or request that the written report of this larger study be shared with you, which may increase your knowledge of how other actors in the system view phosphorus as well as gain knowledge about sustainability recommendations about phosphorus use in the future. This is separate from the interview process, and your interviewer will be able to provide you with more information on this if you are interested.

There are no foreseeable risks or discomforts to your participation. All information obtained in this study will be strictly confidential, your responses will be anonymous unless you wish to be quoted. The results of this research study may be used in reports, presentations, and publications, but the researchers will not identify you unless you so choose. You will also be given a copy of any material that includes your name and/or quotes so that you may review it for accuracy before it is presented or published.

If you would like to allow us to quote you (using your name & affiliation, with an option to review the quote before publication) please sign here:

Sign: ______________________ E-mail: ___________________________ **(Signing on this line and providing contact information signifies your willingness to have your name and affiliation included in the study and allowing me to contact you for follow up purposes).**

I would like to audiotape this interview. The interview will not be recorded without your permission. Please let me know if you do not want the interview to be taped; you also can change your mind after the interview starts, just let me know. Audio recordings of the interview sessions will be kept in a locked cabinet in the School of Sustainability, and will be destroyed after they are transcribed.

If you have any questions concerning the research study, please contact the research team at: Rimjhim Aggarwal, School of Sustainability, Dan Childers, School or Sustainability, or Genevieve Metson, School of Sustainability, Arizona State University, PO Box 875502, Tempe, AZ 85287-5502, (480) 310-3026.

If you have any questions about your rights as a subject/participant in this research, or if you feel you have been placed at risk, you can contact the Chair of the Human Subjects Institutional Review Board, through the ASU Office of

Research Integrity and Assurance, at (480) 965-6788. Please let me know if you wish to be part of the study.

Thank You!

Genevieve Metson

gmetson@asu.edu

Survey-Changes in phosphorus management in alfalfa and cotton production in Maricopa County

Farmer Information

Type of farming operation:

Number of years you have been in the farming business:

Theme 1 – The role and movement of phosphorus on the farm:

1.What varieties of (cotton/alfalfa) do you grow on your farm?

2. Do you use different types (e.g. manure, compost, different synthetic fertilizers) or level of fertilizer on the different varieties?

3.Describe these practices:

4.How have the varieties and fertilizer practices changed over time?

5.Why have they changed?

6.What happens to crop residues? (Are they left there, taken away, solid, used for compost and soil conditioner, or other).

7. Has the fate of crop residues changed in the past 30 years? If so why?

8.Do you test your soils for P content? If so how often, and would you be willing to share such numbers which would remain confidential?

9. Where does your harvest go? Do different parts of your harvest go to different users?

10. If your irrigation water contains reclaimed water, do you know if it contains phosphorus? If it does contain phosphorus has this changed your fertilizer practices?

Theme 2 - Future Scenarios of phosphorus flows in Maricopa:

1. How do you think the role of phosphorus in agriculture in Maricopa County may change in the future?

2. In what way do you think you (or other key agricltural players) could respond to increasing regulation on P in runoff or an increase fertilizer prices and scarcity?

3. Does being in Maricopa county change what you think you can do compared to other farming regions in the US? Does being close to a city change anything? Does being in the desert change anything?

Cooperative Extension Agent and Academic Researcher Information

Name (optional):

Position/Department:

Area of specialty:

Number of years working in the agricultural sector:

Theme 1 – The role and movement of phosphorus on the farm:

1.Do different varieties of alfalfa have different in P requirements, uptake rates, and P concentrations in over plant mass?

2.How do farmers fertilize their cotton and alfalfa fields? What type of fertilizer, application methods, amounts? (e.g. manure, compost, different synthetic fertilizers)

3.How have the varieties and fertilizer practices changed over time?

Technology:

Number of times a year:

Manure:

Compost:

Liquid and solid chemical:

Reclaimed water in irrigation:

Biosolids:

Other:

4.Why have fertilizer practices changed over time? What affects how farmers use phosphorus?

5.What happens to crop residues? (Are they left there, taken away, solid, used for compost and soil conditioner, or other?)

6. Has the fate of crop residues changed in the past 30 years? If so why?

7.Are there publically available test results on soil P content in agricultural fields of Maricopa county? If so at what interval (e.g. annually) and where my I find such data?

9. Where do harvested cotton and alfalfa go? Do different parts of the harvest go to different users?

10. How much irrigation water contains reclaimed water, do you know if it contains phosphorus and it what amount? If it does contaisn phosphorus, do farmers know and has this changed their fertilizer practices?

11. Do you know of publically available datasets that may have specific numbers about the questions asked in this section?

Theme 2 - Future Scenarios of phosphorus flows in Maricopa:

1. How do you think the role of phosphorus in agriculture in Maricopa County may change in the future?

2. What do you see as avenues for the agricultural sector to adapt to increasing in regulation on P in runoff or an increase in fertilizer scarcity and prices?

3. Does being in Maricopa county change what you think you can do compared to other farming regions in the US? Does being close to a city change anything? Does being in the desert change anything?

Regulatory Agency and Water Provider Representative Information

Name (optional):

Agency:

Area of specialty:

Theme 1 – The role and movement of phosphorus on the farm:

1. How has data-collection on nutrient management, and the production and harvest of cotton and afalfa production changed since 1978? What was collected in each year, and what was the reason for changes? How may I access these data?

2.How have regulations fertilizer and nutrient management practices in cotton and alfalfa production (which may be part of dairy production) changed since 1978?

Technology:

Number of fertilizer applications a year:

Manure:

Compost:

Crop Residues:

Liquid and solid chemical:

Reclaimed water in irrigation:

Biosolids:

Other:

3. What affects how your agency views phosphorus?

4. What affects how farmers use and manage phosphorus?

5.Are there publically available test results on soil P content in agricultural fields of Maricopa county? If so at what interval (e.g. annually) and where my I find such data?

6. a) How much irrigation water contains reclaimed water, do you know if it contains phosphorus and it what amount?

b) Has technology changed for processing phosphorus in waste water? If so what are they and what have been there affct?

c) If it does contain phosphorus, do farmers know and has this changed their fertilizer practices?

7. What does a bale of cotton contain (just lint or other stuff)? Is cotton seed included, and where is there USDA record? (question for USDA)

8. Do you know of publically available datasets that may have specific numbers about the questions asked in this section?

Theme 2 - Future Scenarios of phosphorus flows in Maricopa:

1. How do you think the role of phosphorus in agriculture in Maricopa County may change in the future?

2. What do you see as avenues for the agricultural sector to adapt to increasing in problems with P in runoff or an increase in fertilizer scarcity and prices?

3. Does being in Maricopa county change what you think you can do compared to other farming regions in the US? Does being close to a city change anything? Does being in the desert change anything?

Dairy Representative Information

Name (optional):

Agency:

Area of specialty:

Theme 1 – The role and movement of phosphorus on the farm:

1. Where do dairy producers get their alfalfa feed from?

2. If producers own their own land, how do their fertilize their crops?

3. Have fertilizer practices changed in the past 30 years? If so how and why do you think these changes occurred?

4. How is manure from dairy cows used?

5. Have practices around the use of dairy manure changed in the past 30 years? If so how and why?

6. Have regulations about nutrient management in the production of feed, production of milk, and use of manure changed in the past 30 years? If so how and why?

Theme 2 - Future Scenarios of phosphorus flows in Maricopa:

1. How do you think the role of phosphorus in agriculture in Maricopa County may change in the future?

2. What do you see as avenues for the agricultural sector to adapt to increasing in problems with P in runoff or an increase in fertilizer scarcity and prices?

3. Does being in Maricopa county change what you think you can do compared to other farming regions in the US? Does being close to a city change anything? Does being in the desert change anything?

Interview Protocol-

Changes in phosphorus management in alfalfa and cotton production in Maricopa County

Sampling Strategy: expert practitioners.

-sampling by internet search

-sampling by ASU faculty reference

-sampling by reference through key informants (snowball)

Preliminary Interview Questions and Identification of Key Stakeholders

Key informants:

- Cotton, Alfalfa, Dairy farmers (and representatives)
- Extension Agents
- Academic Researchers in the field
- Regulatory agencies (EPA, ADEQ, EPA) and government officials
- Water provider agencies
- UDA representative

Theme 1 - Filling data gaps in phosphorus budgets:

1. What comes to mind when you think about phosphorus? (On your farm, on others farm, in Maricopa in general)

Theme 2 - Future Scenarios of phosphorus flows in Maricopa:

2. How do you think the role of phosphorus in agriculture in Maricopa County may change in the future?

3. In what way do you think you (or other key players) could respond to increasing regulation on P in runoff or in fertilizer prices?

4. Does being in Maricopa county change what you think you can do compared to other farming regions in the US? (does being close to a city change anything? Does being in the desert change anything?)

Information Letter for Interviews and Surveys Anonymous

CHANGES IN PHOSPHORUS MANAGEMENT IN ALFALFA AND COTTON PRODUCTION IN MARICOPA COUNTY

Date

Dear Participant:

I am a graduate student under the direction of Professor Rimjhim in the School of Sustainability at Arizona State University. I am conducting a research study to explore the practices that affect the element phosphorus's flow in the agricultural system of Maricopa County.

I am inviting your participation, which will involve a 30-60 minute interview or the completing of an email survey. The interview and the questions on the survey will be carried out in order to determine your unique perspective of (1) How have P flows in alfalfa- and cotton-production subsystems changed from 1978 to 2008? (2) What are the major determinants of changes in the urban-agricultural P subsystem? (3) How might we increase the recycling and sustainable management of P resources in the urban agricultural environment? Responses to the interview questions will be anonymous, and you as a participant will have the right to skip over questions or stop the interview or survey at any time.

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The main benefits of your participation in the research will be your contribution to the increased understanding how phosphorus, an essential element for plant growth, flows and stock in the region have changed and how they may change in the future.

If you wish, you may choose attend a presentation of the results of this research project, or request that the written report of this larger study be shared with you, which may increase your knowledge of how other actors in the system view phosphorus as well as gain knowledge about sustainability recommendations about phosphorus use in the future. This is separate from the interview process, and your interviewer will be able to provide you with more information on this if you are interested.

There are no foreseeable risks or discomforts to your participation. All information obtained in this study is strictly confidential. Your name, affiliations and quotes, will not be used in the results of the study. The results of this research study may be used in reports, presentations, and publications, but the researchers will not identify you unless you so choose. In order to maintain confidentiality of your records, Genevieve Metson will provide a unique code (in lieu of a name or business name) for each subject's interview entry, and will be the only one to access the confidential information.

I would like to audiotape this interview. The interview will not be recorded without your permission. Please let me know if you do not want the interview to be taped; you also can change your mind after the interview starts, just let me know. Audio recordings of the interview sessions will be kept in a locked cabinet in the School of Sustainability, and will be destroyed after they are transcribed.

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Thank You!

Genevieve Metson

gmetson@asu.edu

APPENDIX C

LITERATURE RANGES OF PHOSPHORUS DATA FOR ALFALFA, COTTON, SOILS, AND FERTILIZERS

Cotton Production

Concentration (plant tissue)	Removal	Uptake	Recommended fertilizer application	Source	Notes
3-0.65 % P dry weight				(Barker & Pilbeam, 2007)	Sufficient in young mature leaves and leaves
	13-14 lbs P2O5 lbs/bale 10 lbs P2O5 lbs/ton			International Plant Nutrient Institute	lint +seeds Burs, stalks, and leaves All based on states other than AZ
4.61 g/kg seed upland 5.39 g/kg seed pima		31 kg P/ha upland 32 kg P/ha pima 2.3 kg/ha for 100kg lint upland 3.3 kg/ha for 100 kg lint upland 11 lbs P/acre to produce 1 bale (460 lbs)		(Unruh & Silvertooth, 1996)	No P in lint. (Bassett & Werkhoven)
			5 ppm should be sufficient for cotton	(R. Norton & Silvertooth, 2006; Silvertooth, Norton, & Galadima, 2001; Thelander & Silvertooth, 1999, 2000)	
			Positive correlation btw yields and P	(E. Norton & Clark, 2004; E. Norton, Clark, & Borrego, 2005; E. R. Norton & Clark, 2003)	
			5 ppm is key	(R. Norton &	

60-90 lbs P2O5/acre is responsive	Silvertooth, 2006)

Alfalfa Production

Concentration (plant tissue)	Removal	Uptake	Recommended fertilizer application	Source	Notes
0.2-0.7 % (sufficient) P	4-6 lbs/ac P 10-15 lbs/ac P2O5		0-60 lbs P2O5/ac Based on soil P concentration	(McKenzie & McKenzie, 2001)	Alberta.
	62-76 P2O5 if you get 5 tons/a yield dry			Canadian fertilizer institute from info in 1998 but published 2001	Canada
	29-39 lbs/ac P			USDA plants.usda.gov/npk/NutrientReport	1st cut bloom with 9.3% moisture
0.25-0.5 % P sufficient				(Barker & Pilbeam, 2007)	Whole plant
0.26-0.7 %					Upper steam
		13 lbs P2O5/ton	-need soil and tissue test -Application before planting -Solid and liquid fertilizer should be the same	(Mikkelsen, 2004)	-can do one big application or every year
0.21-0.22% dry matter				Canadian Dehydrators Association	

Fertilizers

Type	P concentrations	Application type	Extent of application	Source	Notes
Biosolids	3.3 g/100g P dry weight		Need permits since 1996	(Artiola, 2006)	Test in Tuscon
	3% dry weight			ADEQ annual reports	Range: 2-4%
Compost	367.4 mg/kg PO4-P (avg)			(Martin, Slack, Tanksley, & Basso, 2006)	Range: 309-434 (5)
Manure	1274.8 mg/kg PO4-P (avg)		(Kellogg, Lander, & Moffitt, 2000) but it will be by state not	(Martin, et al., 2006)	Range: 1188-1572 (5)

		county (looks at assimilation capacity)		
Chemical on Cotton	Uniform Vs Variable based on GIS and yield		(E. Norton, et al., 2005)	Same yield but VS saves money
Chemical on Alfalfa	Solid Vs liquid		(Mikkelsen, 2004)	Same yield but more P in soils with solid
Chemical on Alfalfa	Pre-seeding application is better	50 lbs/acre per year or 1 application 200 lbs/ac for 4-5 year rotation	(McKenzie & McKenzie, 2001)	(compost and manure also good) uncertainty: in Alberta out of 100 alfalfa fields 70 % had low soil P but only 44% had low tissue P so 26% uncertainty I think).