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Can urban P conservation help to prevent the brown devolution?

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ABSTRACT

Achieving better understanding phosphorus (P) flows through urban ecosystems is needed to conserve P, as non-renewable phosphate rock deposits become depleted and the global human population increases. A baseline mass flow analysis (MFA) for P developed for the Twin Cities Watershed (TCW, which includes most of the Minneapolis-St. Paul metropolitan region) showed that most P input was stored in the system (65%) or leaked from it (31%); only 4% was deliberately exported as useful products. In a realistic, comprehensive conservation scenario P input was reduced by 15%; deliberate export of P in the form of sewage sludge, food waste, and landscape waste was 68% of P input. In this scenario, increased deliberate export was accomplished by decreasing leakage (to 9% of input) and storage (to 23% of input). If used as agricultural fertilizer, the deliberately exported P in the conservation scenario would support about half of the food production required by the TCW. Q1

1. Introduction

Since the 1970s, when evidence of the relationship between phosphorus (P) and lake eutrophication became overwhelming (Schindler, 2006), the main goal of phosphorus (P) management in cities has been to control eutrophication. Eutrophication (nutrient enrichment) increases algae abundance, thereby reducing clarity, shifts the dominance of algae toward blue-greens, and depletes hypolimnetic oxygen, causing release of reduced chemicals (H_2S, Mn^{2+}, Fe^{2+}). Impacts of eutrophication to human well being include reduced recreational enjoyment, reduced property values of lakeshore homes, increased cost of water treatment, and impaired drinking water quality. Exported P also contributes to eutrophication of estuaries, particularly the creation of anoxic zones, which impairs fisheries, often with considerable economic loss (SAB, 2007).

Policies to reduce P pollution from US cities have included expanded use of advanced ("tertiary") wastewater treatment systems and bans on P-containing detergents in 28 states during the 1970s and 1980s, eventually leading to a voluntary industry phase-out (Litke, 1999). In recent years, some states and local governments have also restricted the use of lawn P fertilizers and/or banned the use of P-containing automatic dishwasher detergents (Rosen and Horgan, 2005; USA Today, 2010). Farmers have also become far more efficient it their use of P over the past several decades, reducing their input of P fertilizer while increasing removal of crop P (Bundy, 1998). The agricultural P balance for the Mississippi-Atchafalaya River basin, which was positive most years from 1950–1990 (i.e., more P added to agricultural systems than removed as products) became negative in the 1990s (i.e., the agricultural system was mining P stored in soils) (SAB, 2007). As a result of increased P use efficiency, agricultural P fertilizer use in the US has declined by ~15–20% since the mid-1970s (ERS, 2010).

Despite these efforts, an analysis of P trends in rivers in the US for the period 1993–2004 (Sprague and Lorenz, 2009) revealed more sites with upward trends (24%) than downward trends (16%), with no change at 40% of the sites. P fluxes to the Gulf of Mexico increased by 12% between 1980–1996 and 2001–2003 (SAB, 2007). Hence, it appears that P leakage from our cities and farms continues.

While the motivation to reduce eutrophication is still pressing, a newer and potentially more serious concern is the exhaustion of phosphate rock (Herring and Fantel, 1993; Vaccari, 2009), the source of most P fertilizer. If we do not adopt P conservation policies over the next few decades, the green revolution made possible by industrial fixation of nitrogen (Haber–Bosch process) in the early 20th century (Smil, 2001) could be followed by a "brown devolution" in the mid-to-late 21st century, as rising population and food wealth (e.g., greater meat consumption) collide with diminishing P resources, with devastating consequences for humanity.

Preventing the brown devolution will require us to use less P and to use it more efficiently. This paper focuses on P conservation in urban systems, which may house two-thirds of the world's population by 2030 (FAO, 2001). Although direct P inputs to cities (at

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least in the US) are small relative to agricultural inputs, consumption of food in cities drives agricultural P fertilization. Moreover, in the US at least, there is probably greater future opportunity to conserve P in cities than in agriculture, because P cycling in agricultural systems has already been tightened over the past few decades.

The few studies of urban P cycling that have been conducted indicate that most P entering cities is stored (in landfills or soils) or is exported via wastewater. Tangsubkul et al. (2005) found that 50% of P imported into Sydney, Australia, was stored within the system and that most of the rest was exported as sewage effluent. In a study of 266 counties in the Chesapeake Bay watershed, Russel et al. (2008) found a strong correlation between Net Anthropogenic Phosphorus Index (NAPI, the difference between imported P and net exports of animal and crops) and human population, with NAPI values of 40–80 kg P ha^{-1} yr^{-1} in the counties with densest urban populations. Similarly, Schussler et al. (2007) found in a study of 11 Minnesota watersheds that while P inputs (kg ha^{-1} yr^{-1}) were higher in agricultural watersheds than in urbanized watersheds, net P retention was highest in more urbanized watersheds, because there was little "deliberate export" of P in the form of agricultural products.

This study examines P balances for the Twin Cites Watershed (TCW), which includes most of the Minneapolis-St. Paul (Minnesota, USA) metropolitan region. P balances include a baseline P balance (for 2000), and three conservation scenarios (reduced input; reduced storage; and reduced leakage), followed by a comprehensive conservation scenario that includes all three conservation approaches. The comprehensive conservation scenario reduced P input by 15%, reduced P storage by 71%, and reduced P leakage by 74%, while increasing deliberate P export by 1200%. The P supplied by the comprehensive conservation scenario would be sufficient to grow about half of the food needed by the TCW.

2. Theory

Mass flow analysis (MFA), the process of tracking the movement of pollutants through ecosystems, can be a valuable tool for gaining insights regarding management of pollution in cities and agricultural ecosystems. MFA has become an integral tool to industry ecology, but is only now gaining ground as a technique to analyze sources and fates of pollutants in urban ecosystems (Baker, 2009). Early applications of MFA to cities include Boyd et al. (1981) and Faerge et al. (2001). In the past decade, the approach has been used with increasing frequency to not only describe urban systems, but to develop innovative solutions to pollution problems. Some examples include the construction of a detailed N balance for Phoenix, Arizona, used to envision a novel approach for reducing groundwater nitrate contamination (Baker et al., 2001); an analysis of pathways of N and P in residential water systems (Gray and Becker, 2002), the development of salt balances for five southwester water utilities to identify potential for reducing salinity in recycled wastewater (Thompson et al., 2006); the use of a urban-agricultural N balance to quantify the effect of urban diet changes on coupled agricultural and urban systems (Baker and Brezonik, 2007); and the development of salt balances for the Twin Cities, Minnesota urban region to quantify accumulation rates (Novotny et al., 2009). MFA has also been used to quantify C, N, and P fluxes for large numbers of individual households (Baker et al., 2007; Fissore et al., 2010).

3. Materials and methods

The system boundary for the TCW was the watershed bounding most of the urbanized region (Fig. 1), bounded on the upstream by the Mississippi River at Anoka, on the north, and the Minnesota River at Jordan on the west, and on the downstream side by the

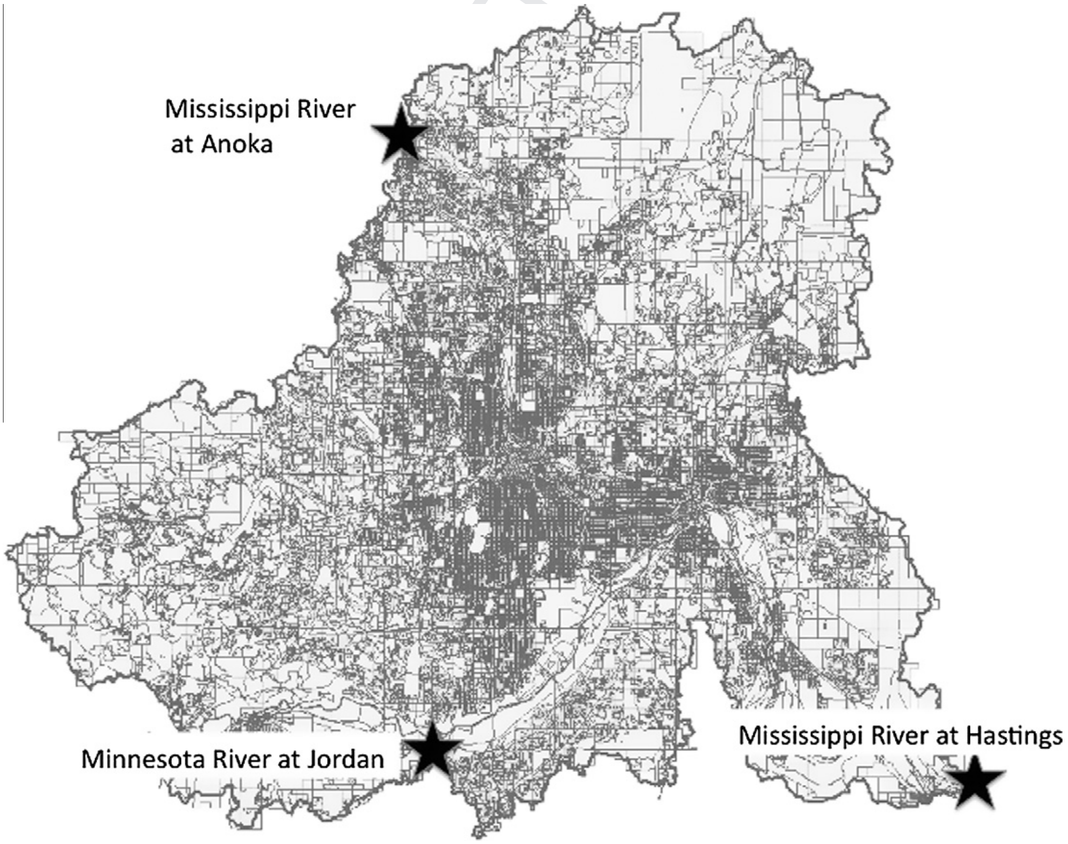

Fig. 1. Map of the Twin Cities Watershed (TCW), showing watershed boundaries, key river sampling sites, and Census blocks (roughly proportional to population density).

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Table 1
Characteristics of the TCW.

Characteristic	Value
Population	2.1 million
Number of farm animals	
Number of dogs	471,000
Number of cats	596,000
Number cows	2700
Number of hogs	5600
Area, km^2	3011
Land use (%)	
Residential	33
Agriculture	9
Water, undeveloped	30
Commercial, institutional, industrial	12
Transportation	4
Parks and golf	12

Mississippi River at Hastings (Fig. 1). Key characteristics of the TCW are shown in Table 1.

Methods the watershed P balance generally follow from methods used to develop a regional N balance for Phoenix, Arizona (Baker et al., 2001) and, more generally, Baker (2009). Additional documentation of methods to calculate P fluxes associated with households (e.g., human and pet food; landscape wastes) can be found in Baker et al. (2007) and Fissore et al. (2010). The latter paper includes an extensive "supplemental methods" section.

The baseline MFA presented here represents the TCW in "ca. 2000" as nearly as possible. Export of stream P from the urban watershed is an estimate from long-term averages or "normal" conditions computed by Kloiber (2006). GIS layers of land cover, land use, and the regional sewershed were obtained from a regional governmental organization, Met Council, and watershed population was determined from US Census block level data. Population served by septic systems was determined by subtracting the population within the sewershed from the total watershed population. P moving to septic systems was considered to be "stored"; P moving to municipal sanitary sewers was routed to wastewater treatment plants (discussed below).

Human food consumption was calculated from national studies of food consumption for the current period (USDA, 2005), multiplied by the age- and sex-stratified population for the watershed. Scenarios involving reduced human food input were based on the US diet in 1977–1978 (USDA, 1978). Pet food input to the system was calculated using the approach outlined in Fissore et al. (2010), using a national estimate of pet incidence (PFI, 2003) and TCW population to derive the total number of dogs and cats (Table 1). Average weights of 30 kg for dogs and 5 kg for cats were assumed. Because there is little food production within the TCW, both human and pet foods were considered to be imported.

Lawn P fertilization was estimated from a state-wide assessment of lawn fertilizer (MDA, 2007) by computing a per capita lawn P fertilization rate for the state and scaling this to the TCW population for the year 2003, before Minnesota enacted a lawn P fertilizer restriction. Atmospheric P deposition (wet + dry for an average year) was based on a study by (Barr, 2007) using the average of values for the Upper Mississippi River and the Lower Mississippi River (0.35 kg ha^{-1} yr^{-1}).

P loadings to sewage treatment plants were calculated as the product of monthly P concentration times flow for influent sewage, summed for the year 2000, and then summed across the seven metro region sewage treatment plants, using data obtained from Met Council. Discharge of effluent P was computed in a similar manner, using data for the outflows from each plant. Average P removal was 56%. P removed from sewage was assumed to enter sludge. This sludge is then ashed and transported to landfills, where it is buried.

All P in consumed human food was assumed to enter sewage. The difference between P in human excretion and P input to the sewage treatment plants (non-fecal P) includes garbage grinder wastes, automatic dishwasher detergents, and dentrifices. Per capita inputs for these components were estimated by Barr (2007) and Baker et al. (2007), refined slightly in Fissore et al. (2010).

The flux of P in solid waste sent to landfills, based on Beck (1999), was considered P storage. In additional to untreated solid waste, the City of Minneapolis incinerates its waste and landfills the ash, so this was added to the "landfill" flux. Finally, about 30% of food waste is diverted before it enters landfills for animal feed and other purposes (SWMCB, 2007). This flux was counted as a separate export from the system. Most yard waste that leaves private property is composted. The flux of yard waste to the compost system was estimated using a household level export rate of 0.1 kg P per household per year for single-family, detached homes (Fissore et al., 2010), which comprise 72% of all households in the Twin Cities region and have an average of 2.6 occupants ∗(USHUD, 2007). A small fraction of yard wasted enters landfills (it is illegal to dispose of yard waste in landfills, but some enters anyway), but most of the rest is composted. Because there are many compost sites, operated by multiple entities (individual municipalities, counties, and private contractors), it was difficult to estimate the fate of compost. For the City of St. Paul, 95% of compost is exported to agricultural land outside the metropolitan region; hence this value was used to represent the export fraction for compost.

P fluxes throughout agricultural land in the watershed were calculated by assuming that agriculture within the TC watershed was similar as agricultural land in the larger 7-county metro region, hence fluxes could be scaled down from county-level data (number of farm animals, acreage of crops, fertilization rates for each crop, etc.) to estimate the distribution of crops and farm animals (NASS, 2002; MDA, 2003) in the TC watershed. P use efficiency for farm animals (mainly dairy cows and hogs) were based on a whole "whole herd" approach developed by (Schussler et al., 2007), yielding values of 35% of dairy cows and 50% for hogs. Animals and animal products (mostly milk, beef, and hogs) were assumed to be exported from the TCW for processing. All manure P was considered to be recycled to crops. The net direction of crop P flux was determined by comparing the feed requirement of farm animals with crop production in the watershed, both in terms of P. If crop P exceeded animal feed needs, the excess crop P was exported from the watershed. If crop P was less than needed for farm animals, the deficit was supplied by imported animal feed (e.g., grains).

4. Results

4.1. Baseline (2000) TCW P balance

4.1.1. P inputs

Table 2 shows that the major P inputs to the TCW are imported human food, both food that is directly consumed (1.16 Gg P yr^{-1}) and food that is imported but wasted (0.51 Gg yr^{-1}). Together, these account for 41% of total P inputs to system. Calculated food waste (31% of total food input) agrees well with Kantor et al. (1997), who found that 27% the edible food supply in the US is wasted.

The next largest P input was P-containing chemicals that enter sewage, other than human excretion and garbage disposal waste. A study by (Barr, 2007) reported that these include dentrifices (0.012 kg cap^{-1} yr^{-1}) and automatic dishwasher detergents (0.125 kg P capita^{-1} yr^{-1}, with 68% coming from residences and the rest from commercial dishwashing), anticorrosion agents added to water supply, and other commercial and industrial sources.

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Table 2
Current P balance for the TCW.

Inputs	P flux (Gg yr^{-1})	% of total
Human food consumed	1.16	28.5
P-containing chemicals that enter sewage	1.37	33.7
Wasted human food	0.51	12.5
Pet food	0.55	13.5
Agricultural fertilizer	0.22	5.4
Turf fertilizer	0.12	2.9
Atmospheric deposition	0.11	2.7
Feed for farm animals	0.04	1.0
Total input	4.07	100.2
Outputs		
Wastewater effluent	1.14	79.7
Stream export	0.11	7.7
Animal products	0.12	8.4
Diverted food waste (to farms)	0.03	2.1
Landscape compost	0.02	1.4
Total output	1.43	99.3
Storage		
Sewage sludge	1.46	55.3
Landfill food waste	0.25	9.5
Septic system storage	0.23	8.7
Landfill landscape waste	0.05	1.9
Ecosystem storage (mostly soils)	0.66	25.0
Total storage	2.64	100.4

Pet food was the third major P input, accounting for 14% of total P inputs to the region, more than twice as much as turf fertilization and atmospheric deposition combined. Finally, inputs to agriculture within the urban region, including fertilizer and animal feed, was 0.26 Gg P yr^{-1}, about 6% of total P input to the region. Agricultural P fluxes were small: agricultural fertilizer and imported feed for farm animals together accounted for only 6% of total P input to the TCW.

4.1.2. P exports

Table 2 shows that 1.43 Gg P yr^{-1}, about 36% of input P is exported from the urban system. P exported as wastewater effluent plus stream flow to the Mississippi River together account for 31% of total P input. This P export would be considered "leakage" that has no useful purpose.

Small amounts of P are exported as useful products. These "deliberate exports" include landscape wastes, animal products, and some waste food that is diverted from the solid waste stream to become animal food, either directly or through processing. Deliberate export account for only 0.17 Gg P yr^{-1}, about 4% of P input.

4.1.3. Storage

Sixty-four percent of P entering urban region is stored, either within the urban system or in landfills outside the urban boundaries that receive urban waste. Sewage sludge is the largest flux, accounting for 36% of all P entering the urban system. Most of the rest of stored P enters landfills (0.25 Gg yr^{-1} as food waste and 0.05 Gg yr^{-1} as landscape waste). Ecosystem storage (ES), computed by difference (ES = input − export − accounted storage) was 0.66 Gg yr^{-1}, about 14% of input P.

4.1.4. P balance summary

In summary, the current P balance for the TCW is highly inefficient. Most P entering the system is either leaked to the Mississippi River (31%) or stored in landfills or septic systems (49% of input). Another 15% is stored in soils and plants, and only 4% is deliberately exported as useful products.

Table 3
Calculated P fluxes for conservation scenarios I–IV. Units are Gg yr^{-1}.

–	Input	Storage	Deliberate export	Leakage
Baseline	4.07	2.64	0.18	1.25
I. Reduced input	3.44	2.1	0.20	1.14
II. Reduced storage	4.07	0.90	1.92	1.25
III. Reduced leakage	4.07	3.52	0.18	0.37
IV. Comprehensive, I–III	3.44	0.78	2.34	0.32

4.2. P conservation strategies

Four P conservation strategies were developed: (I) reduced P input; (II) reuse of stored P, (III) reduced leakage; and (IV) a comprehensive strategy, combining I–III (Table 3). Reductions are focused on major flux terms (generally > 10% of input), and were chosen to be realistic based on current technology and lifestyles.

4.2.1. Scenario I: reduced P inputs

For this scenario, consumed human food input was reduced to correspond to the US diet in 1977–1978, based on data from the Continuing Survey of Foods (USDA, 1978). This reduced consumed food P by 12%. Imported food waste was reduced by the same percentage. P in automatic dishwashing detergent was eliminated, an act that has taken place in reality in the form of a 2010 law. Dog food was reduced by 50%; this could be accomplished over time by selecting smaller breeds of dogs. Finally, lawn P fertilizer is reduced to 0 (to comply with the current Minnesota law). This scenario reduced P inputs to the TC watershed by 15% and slightly decreased storage and leakage (Table 3).

4.2.2. Scenario II. Reuse of stored P

This scenario diverted all food waste entering landfills to a deliberate export. This diversion could be done by through a combination of the following: composting municipal food waste, then exporting the compost; shipping it directly to farms for animal food; processing it to form animal feed; and diverting ash from food waste that was combusted in a solid waste incinerator located in downtown Minneapolis. All of these processes, except the last, are currently being done for parts of the food waste stream. In this scenario all ash from sewage sludge and from solid waste incineration was also exported from the TCW, to be applied to agricultural land. Finally, lawn waste now entering landfills was diverted to deliberate export. These measures reduced storage within the urban system by 66% and increased deliberate export by a factor of 11 (Table 3).

4.2.3. Scenario III. Reduce leakage

In this scenario, P removal efficiency for all wastewater treatment plants in the region was increased from 56% (measured in 2000) to 90% (currently being achieved at the largest treatment plant, but not at the smaller plants). No change was made in stream P leakage, because there appears to be no empirical evidence of success in achieving large reductions in P loading in urban streams as the result of deliberate management, other than through changes in land use. Upgrading wastewater treatment reduced leakage by 75%.

4.2.4. Scenario IV. Comprehensive P conservation scenario

In this scenario, the three previous scenarios were combined.

5. Discussion

5.1. Realism of P conservation scenarios I–IV

P conservation requires three broad elements: reduced P inputs, reduced storage, with a shift toward deliberate export of P for

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useful purposes, and reduced leakage, mainly through improved sewage treatment.

The comprehensive conservation scenario (IV in Table 3) developed here was intended to be reasonable and practical. All types of reuse envisioned here are being employed for at least part of the waste stream; the conservation scenario merely increases the fraction of the waste stream that becomes deliberate export for practical uses. On the input side, the conservation diet is merely one that Americans actually ate 30 years ago, prior to the obesity epidemic that has grown since that time. With regard to reducing lawn fertilizer P inputs, Minnesota has enacted a law prohibiting use of lawn P fertilizers (with some exceptions). In Minnesota, at least, the law has been readily accepted, though apparently not universally obeyed (MDA, 2007). Similarly, Minnesota, along with 16 other states, has passed laws to reduce the P in automatic dishwasher detergents (USAToday, 2010). Finally, the conservation scenario included reduction in size of dogs. This probably could not be accomplished by regulation, but possibly through an education campaign. Citizens might be motivated to reduce pet wastes because many local watersheds drain directly to highly valued local lakes. Fissore et al. (2010) found that with Minnesota's lawn P fertilizer law in effect, pet excretion is now the main source of P to the landscapes of owner-occupied houses.

More drastic conservation measures could be envisioned. In particular, adoption of a vegetation diet would reduce P use in upstream agricultural systems, by reducing P losses associated with conversion of animal feed to animal products (Cordell et al., 2009). However, only 3% of Americans report that they are vegetarians, and only 0.3% report being vegan (Vegetarian, 2008). Furthermore, most vegetarians consume animal products, such as fish, milk, cheese, and eggs, all of which involve conversion of plant P to animal P, with associated inefficiencies. More realistic P conservation scenarios would involve modest changes in diet, such as reduction in animal products among those consuming traditional diets.

5.2. Effect of P conservation scenario on the TCW's P balance

Adoption of a comprehensive P conservation scenario (Table 3) would increase the percentage of input P that is reused from 4% to 68%, while reducing leakage from 31% of input to 9%. Of particular importance is the increase in deliberate export of P, from 0.18 Gg yr^{-1} in the baseline scenario to 2.34 Gg yr^{-1} in the comprehensive conservation scenario. After subtracting 0.12 Gg yr^{-1} that is exported from the urban system as animal products in both scenarios, the amount of deliberate P export that is could be recycled to agricultural systems is 0.06 Gg yr^{-1} (baseline) and 2.22 Gg yr^{-1} (comprehensive conservation scenario)(Table 4, line 2). The impact of reused urban P in the context of agricultural P inputs can be coarsely estimated from the national P flow analysis of (Suh and Lee, this issue). Their analysis shows that 1892 Gg P yr^{-1} are added to US crops that are converted to food, which produce food containing 745 Gg P yr^{-1}, a ratio of fertilizer: food of 2.5. Dividing the value for P available to agriculture (Table 4, line 2) by 2.5 yields the amount of food that could be supported by reused P (Table 4, line 3). Finally, line 4 shows the percent of the urban food supply that could be supported by reused P.

Table 4
Effect of adopting the P conservation scenario on the TCW's P balance.

	Baseline	Conservation
1. Food P	2.26	1.88
2. Reused P available for export to agriculture	0.06	2.22
3. Food P supported by reused urban P	0.03	0.89
4. % of urban food supported by reused urban P	1.3	47

This analysis shows that reused P in the comprehensive P conservation scenario could support 47% of the food supply for the TCW system, compared with only 1% in the baseline scenario. The conclusion of this analysis is that reusing urban P for agricultural production could be an important strategy for sustaining urban food supply in the face of dwindling phosphate rock resources.

One practical limitation to operationalizing a P conservation scenario is the cost of transporting reused P to agricultural lands. Most forms of reused P (e.g., food wastes, compost) have fairly low P content, hence are much heavier to transport that high-P fertilizers. A P conservation scenario would likely be feasible only for nearby agriculture. Thus, one consequence of our response to exhaustion of mined phosphate rock will likely be more peri-urban agriculture.

P conservation would have several ancillary benefits. One of the most important would be decreased leakage of P to aquatic ecosystems, which could reverse eutrophication of lakes and estuaries in or near cities. A second would be a reduction of landfill volumes, decreasing the amount of land needed for landfills in the future and the cost of transporting solid waste to ever-increasing distances from cities. A third would be facilitation of local agriculture, through provision of reused P.

5.3. Research needs

Given the growing importance of P conservation in the future, more research is needed to develop P conservation strategies. Although all of the conservation measures included in this study have been implemented on at least a small scale, the economic, ecological, and social implications of reengineering the P cycle of urban regions on a comprehensive scale needs to be studied. Because the sustainability implications of P conservation are likely site-specific, the ideal study would include a number of cities that span a range of conditions. Of particular importance is a better understanding of the fate of food wastes throughout the crop-to-food system, and a better understanding of how nuanced diet choices and particular food production systems influence P fluxes between cities and agricultural systems. Although urban residents are not likely to make profound changes in diet (like becoming vegan), they do make modest changes, often with some government persuasion. For example, from 1970 to 1974 to 1995, American citizens reduced consumption of red meat by 12%, while increasing chicken consumption by 89%; and switched from whole milk (63% reduction) to 1% milk (423% increase)(Harnack et al., 2000). These types of modest diet changes can make a very significant difference in nutrient requirements for agricultural systems supplying cities (Baker and Brezonik, 2007; Suh and Lee, in review for this issue) and hence need to be understood, especially in the context of the closer physical linkage between agricultural systems and urban systems that is likely to evolve to conserve P.

6. Conclusion

As we start to mobilize for the task of conserving P to slow the exhaustion rate of global phosphate rock, urban P balances can be used to shape conservation strategies. P conservation would generally include three elements: reducing inputs, reducing leakage, and reusing P wastes. For the TCW, a comprehensive, practical P conservation strategy reduced P inputs by 15%, reduced leakage to aquatic systems by 74%, and reduced storage by 70%, while increasing deliberate export by 1200%. P exported from the TCW to farmland would be sufficient to support nearly half of the food supply for TCW. Implementing P conservation on a large scale will require considerable research. Research to understand P conservation at the national level should be started very soon so that we can

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acquire knowledge regarding sustainable P conservation that could be implemented before the situation becomes a crisis.

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