Pathways and Management of Phosphorus in Urban Areas

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Summary

Due to the finite nature of mineral phosphorus reserves, effective management of anthropogenic phosphorus flows is currently under investigation by the international research community. This article emphasizes the importance of urban phosphorus flows, which are often marginalized due to the greater magnitude of agricultural phosphorus flows. A study on phosphorus flows in Gothenburg, Sweden, points out the potential role of solid waste in nutrient management, as the amounts of phosphorus in solid waste and in wastewater were found to be equal. Importation of food commodities accounts for 50% of the total inflow of phosphorus, and food waste is a major contributor of phosphorus to solid waste. The results suggest that solid waste incineration residues represent a large underestimated sink of phosphorus. Focusing on wastewater as the sole source of recovered phosphorus is not sufficient. The Swedish national goal on phosphorus recycling, which is limited to sewage sludge, targets only a part of the total phosphorus flow that can potentially be recovered. In contrast to previous studies, agricultural flows in Gothenburg were marginal compared to flows related to the urban waste management infrastructure. We emphasize the need for debate on preferable routes for disposal of waste with a high phosphorus content. Both recovery potential and usefulness of the recovered product for agricultural purposes have to be considered. Impacts of five waste management strategies on phosphorus flows were evaluated: incineration of all the waste, comprehensive food waste separation, installation of kitchen grinders, urine diversion, and separation of blackwater and food waste.

Introduction

Modern agriculture depends on the use of fertilizer for food, feed, fiber, and biofuels production. Nitrogen (N) and phosphorus (P), two major constituents of fertilizer, are both essential to life and nonsubstitutable; phosphate ore is also a nonrenewable resource. Mining of phosphate ore has been increasing exponentially since the beginning of the Green Revolution in the 1940s and correlates with world population growth. Worldwide, about 90% of the demand for phosphate ore is driven by the production of mineral fertilizers and animal feed additives for agriculture. Currently there is an ongoing debate on the finite nature of phosphorus resources and potential future phosphorus scarcity. Therefore various authors advocate economical use and recycling of phosphorus (Cordell et al. 2009; Heffer 2006). While experts disagree on the magnitude of available phosphorus resources, the demand for fertilizer is likely to increase further due to continuing population growth, the effort to eradicate hunger and malnutrition, a potential shift toward more meat-based diets, and increasing demand for biofuels. In addition, environmental damage caused by the mining and

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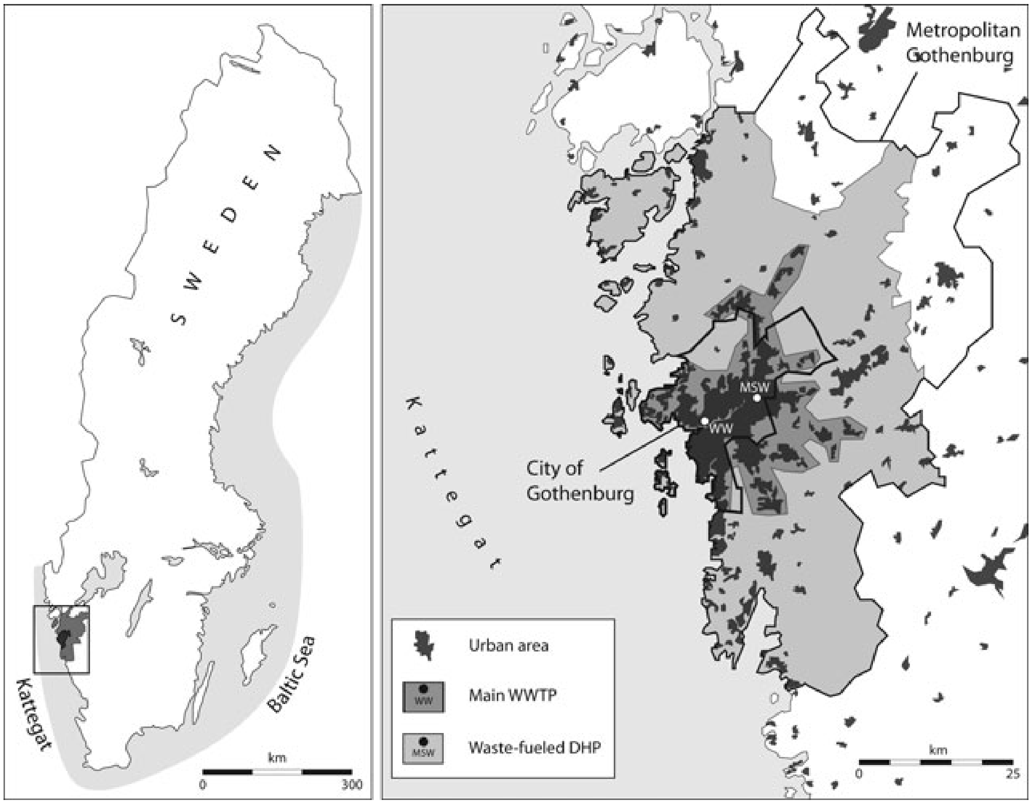

Figure 1 (Left) The location of the city of Gothenburg, Sweden, and metropolitan Gothenburg. (Right) The collection area of main waste treatment facilities located in the city of Gothenburg.

production of phosphate fertilizer is likely to be aggravated due to a declining quality of phosphate ore.

It has been stated that a prime requirement for rational management of phosphorus resources is better quantification of all flows and pathways: globally, regionally, nationally, and locally (Dawson and Hilton 2011). On a global scale, the main phosphorus flows are related to the production and application of mineral fertilizers and, due to considerable losses in agriculture, only about a third of mined phosphorus reaches urban areas (Cordell et al. 2009). However, we maintain that studies on a city level are essential, as cities often serve as final sinks for phosphorus and substantial amounts may potentially accumulate in urban areas. Cities are major socioeconomic entities, as more than 50% of the global population lives in cities and the urban population is forecasted to double by 2050.

Studies of phosphorus flows at a city scale are scarce. Studies of cities in China, Thailand, and Vietnam focus on agriculture and animal stock (Færge et al. 2001; Li et al. 2010; Montangero et al. 2007; Yuan et al. 2011). In contrast, agriculture is often disconnected from cities in developed countries. Phosphorus flows and related management objectives are therefore different, with pollution prevention in developing countries and nutrient recovery in developed countries. The latest study for developed countries is for the period 1870–2000 in Linköping, Sweden, and is limited to the food production and consumption chain (Neset et al. 2008). One of the main conclusions of the study was the trend of increasing urban phosphorus flows due to changes in diets.

This study investigates phosphorus flows at a city level using Gothenburg as an example. The main research questions were

- Which are the main flows and sinks of phosphorus in a city?
- Which are alternative phosphorus pathways in Gothenburg and what is their impact on recycling goals?

Methods and Study Area

Gothenburg is the second largest city in Sweden and is situated on the west coast (see figure 1). The population of the 13 municipalities forming metropolitan Gothenburg is 916,825 (9.8% of Sweden's population), whereas 506,730 (5.4% of Sweden's population) live in the city of Gothenburg, which is also a municipality. Gothenburg was chosen due to ongoing discussions among stakeholders regarding potential changes in the municipal waste management infrastructure toward more favorable pathways for nutrients. The manufacturing industry located within Gothenburg includes a chemical company, an automobile manufacturer, a ball bearing manufacturer, two refineries, a smaller textile manufacturer, and a plastics manufacturer. The food industry includes fisheries, a dairy company, a potato chips producer, charcuteries, and one large and several small bakeries. A few small farms, mostly producing vegetables and meat products for the local market, represent agricultural production.

The phosphorus flows were studied by means of a material flow analysis (MFA). The reference year for this study is the year 2009, and the spatial system boundary is the geographical border of the municipality of Gothenburg. It should be noted, however, that the collection area for the main municipal wastewater treatment plant (WWTP) and municipal solid waste treatment plant (SWTP) located within the geographical borders of the municipality of Gothenburg extends well beyond the municipality's geographical borders (see figure 1). Five adjacent municipalities are partly connected to the WWTP, and solid waste is collected from 10 neighboring Swedish municipalities and is sometimes imported from Norway. The inputs of wastewater and solid waste from these municipalities were treated as imports.

Estimation of the amount of phosphorus contained in goods was restricted to a limited number of goods, as neither supply nor demand estimates were available for every type of good. Data on the origin and composition of solid waste were hard to interpret due to a partial lack of information on solid waste pathways and inconsistent definition of the term "household waste." Reliance on various data sources and inconsistent usage of terminology can introduce redundancy and overlap in budget components, resulting in potential double counting. If estimates of the same flow could be based on different data sources, potential inconsistencies were investigated.

Flows of Phosphorus in Gothenburg

Human Activities and the Built Environment

Ingestion of Food Commodities

Food commodities for human consumption constitute a major flow of phosphorus due to their relatively high phosphorus content and the high turnover rate. Detailed data on imports, exports, and local production of food commodities were not available. Therefore the amount of phosphorus contained in food commodities consumed was estimated based on dietary phosphorus intake. Phosphorus intake in Gothenburg was assumed to be similar to the intake in Malmö, a nearby city, for which the intake has been estimated to be 1,182 milligrams of phosphorus per day (mg P/day) for women and 1,505 mg P/day for men (Welch et al. 2009). Children up to the age of 10 years were assumed to take up half of this value. Based on the daily intake, gender distribution (50.44% women), and age distribution (11% are less than 10 years old), a total phosphorus intake of 235 tonnes[1] of phosphorus per year (t P/yr) (<F01>) was calculated. Nearly 100% of the phosphorus intake via food is excreted (<F18>) (Welch et al. 2009). Commuting patterns were not accounted for, as most commuting takes place within areas connected to the main WWTP. Phosphorus contained in commuters' excreta is therefore accounted for as system internal discharge or as imports from adjacent municipalities; the total phosphorus flow toward the WWTP remains unaffected.

Food Waste

Of the food imported for Swedish households, about 30% is wasted prior to consumption: 5% to 10% in retail and distribution and 20% to 35% by consumers (Skjöldebrand 2008). This would suggest a phosphorus flow of approximately 100 t P/yr (<F02>) embodied in waste food: 75 t P/yr from households and 25 t P/yr from food stores in Gothenburg (<F20*>) (composites of a flow are denoted <F#*>).

Detergents and Personal Care Products

In 2009 the amount of phosphates contained in detergents used in Sweden was 3,268 t (Swedish Chemicals Agency 2010). Based on a phosphorus content of phosphates of 25%, this corresponds to a phosphorus flow of 817 t P/yr for Sweden, or 44 t P/yr (<F03>) for Gothenburg (5.4%). It is assumed that all detergents are discharged via wastewater disposal pathways after usage (<F19*>). An estimation based on a German study (Nolde 2000) indicated that a population equal to that of Gothenburg would discharge approximately 3 t P/yr (<F19*>) contained in personal care products via showers, bathtubs, and hand-washing basins.

Pet Food

The estimation of pet food intake was limited to cats and dogs. In large Swedish cities there are 28 dogs and 58 cats per 1,000 inhabitants (SCB 2006). We assumed an average live weight of 20 kilograms (kg) for dogs and 4 kg for cats,[2] respectively. The phosphorus intake of a dog weighing 20 kg is 1.2 kilograms of phosphorus per year (kg P/yr) (Baker et al. 2007). Assuming similar food requirements and food composition, the phosphorus intake of a cat weighing 4 kg is 0.27 kg P/yr. The total phosphorus intake of 14,000 dogs and 30,000 cats in Gothenburg thus amounts to 25 t P/yr. Assuming that 10% of imported pet food is wasted (3 t P/yr; <F20*>), the total flow of phosphorus embodied in pet food entering the urban area is on the order of 28 t P/yr (<F07>). It is furthermore assumed that 60% of pet excreta (15 t P/yr; <F20*>) are collected and disposed of via the municipal solid waste collection system, whereas the remaining 40% (10 t P/yr; <F17>) are deposited on nonarable land.

Newspaper and Packaging

In 2009 a total of 646,709 t of paper packaging and 460,000 t of newspaper were put on the Swedish market, of which 74.2% and 91% were recycled, respectively (FTIAB 2011a). Assuming a phosphorus content of 0.24 grams of phosphorus per kilogram of dry solid (g P/kg DS) for paper products[3] (Sokka et al. 2004), the replacement of paper packaging and newspapers not recycled (<F20*>) induces a net flow of phosphorus (<F05*>) on the order of 3 t P/yr for Gothenburg (5.4% of Sweden). In 2006 a total of 301,628 t of wooden packaging were put on the Swedish market, of which 251,498 t were incinerated (FTIAB 2011b). Assuming a phosphorus content of

Table 1 Phosphorus content and flow from livestock manure for Gothenburg, Sweden, 2009

Category	*Number of individuals*[a]	*P in manure per individual*[b] *(kg P/yr)*	*P in manure (t P/yr)*	*P in imported feed (t P/yr)*	*P in fodder (t P/yr)*
Horses	2,016	8.9	17.9	0	22.4
Dairy cows	153	17.0	2.6	0.1	3.2
Beef cows	399	12.0	4.8	0.7	5.3
Bulls	343	8.0	2.7	0	4.5
Calves	465	3.1	1.4	0	1.8
Pigs	1,147	2.5	2.9	0.1	3.5
Sheep	552	1.5	0.8	0	1.0
Chicken	240	0.13	0.0	0	0
Total			35	1	42

Notes: [a]Jordbruksverket (2010).
[b]Jordbruksverket (2007).
P = phosphorus; kg P/yr = kilograms of phosphorus per year; t P/yr = tonnes of phosphorus per year.

0.31 g P/kg DS for wood products (Sokka et al. 2004), the replacement of wood packages not recycled (<F20*>) induces a net flow of phosphorus (<F06*>) on the order of 4 t P/yr for Gothenburg.

Atmospheric Deposition and Stormwater Runoff

The area of the municipality of Gothenburg is 44,900 hectares (ha). The input of phosphorus via atmospheric deposition was estimated to be on the order of 3 t P/yr (<F38>), assuming a deposition rate of 5.8 milligrams of phosphorus per square meter per year (mg P/m^2/yr) based on a study for a sampling location close to Gothenburg (Knulst 2001).[4] Both stormwater runoff from arable land and nonarable land has been quantified by the environmental administration of the municipality of Gothenburg (Göteborg Stad 2010). Agricultural runoff transports 3 t P/yr (<F50>) toward the aquatic environment; runoff from nonagricultural land (not draining into a sewer system) contributes 6 t P/yr (<F49>). Stormwater runoff through the sewer system contributes 4 t P/yr (<F22>) based on the volume of stormwater input estimated by the WWTP and an average phosphorus concentration of 0.4 milligrams per liter (mg/l) (Malmqvist et al. 1994; Matsson 2011).

Flows Related to Agricultural Activities

Arable land located within the city borders is predominantly used for fodder production (Göteborg Stad 2010). The flow of phosphorus contained in mineral fertilizers was estimated to be 16 t P/yr (<F12> = <F25>) based on the area of arable land of 3,036 ha and application statistics for the county in 2009: 60% of the area is fertilized with an average of 8.8 kilograms of phosphorus per hectare per year (kg P/ha/yr) from mineral fertilizer (SCB 2009). There are no statistics on mineral fertilizer use for nonagricultural purposes.

The amount of phosphorus contained in animal manure was estimated to be 35 t P/yr (<F26>) based on the number of animals, annual manure production, and its phosphorus content (see table 1). According to the Federation of Swedish Farmers, all manure is returned to arable land (Larsson 2011). Eighty percent of the phosphorus ingested by cattle is excreted (Wells 1996) and the amount of phosphorus in consumed feed and fodder is 43 t P/yr. Conserved grass makes up the major portion of fodder for horses, sheep, and dairy and beef cows, while a minor part is cereals and rapeseed (Lindberg 2012). Grass, cereals, and rapeseed are locally produced. Livestock also receive a protein supplement through soy, which is imported. The fraction of the diet obtained through soy for different animals in 2009 was found to be 11% for beef cows, 3% for dairy cows and pigs, and 16% for chickens (Emanuelson 2010); no information was found on sheep. Estimated as the sum of corresponding fractions of the total flow, the imported phosphorus with soy is 1 t P/yr (<F13>).

The difference of 8 t P/yr between feed and manure is contained in either animal products or in bones and carcasses. The amount of phosphorus embodied in bones and carcasses disposed of through solid waste is assumed to be 1 t P/yr (<F24>); the amount of phosphorus contained in animal products is assumed to be 7 t P/yr (<F11>). The amount of phosphorus contained in locally produced vegetables for human consumption is assumed to be negligible.

Waste Collection

Wastewater Collection

In the municipality of Gothenburg, 502,000 people (99% of the population) are connected to the municipal sewer system; 147,000 people are connected from the surrounding municipalities (Gryaab 2007, 2010). Most industries in Gothenburg are also connected to the main WWTP and information on the annual flow as well as quality of the discharge has been obtained from the operator of the WWTP: industrial discharges within the municipality of Gothenburg contribute a phosphorus load of 5.3 t P/yr (<F21>) and industries located in adjacent municipalities make no significant contribution (Matsson 2011). Assuming similar per capita discharge (0.55 kilograms of phosphorus per capita per year [kg P/cap/yr]) in all municipalities connected to the main WWTP, 80 t P/yr (<F16>) are discharged to the sewer system by households in neighboring municipalities.

Table 2 Amount and category of solid waste disposed of by households in Gothenburg, Sweden, 2009[a]

Waste category	*Amount (t)*	*Dryness (%)*	*P content (g P/kg DS)*	*P content (t P)*
Residual waste	122,764			60.6[b]
Organic waste (central composting)	11,061	35	4	15.5
Organic waste (home composting)	4,000	35	4	5.6
Paper and cardboard	24,895	100	0.24	6.0
Glass, metal and plastic	10,794			
Dangerous waste and WEEE	7,623			
Bulky goods				
Wood products	11,880	81	0.31	3.0
Combustible household waste	10,160	100	0.15	1.5
Noncombustible household waste	13,647			
Total	216,824			91.8

Notes: [a]Porse (2011).
[b]Sum of table 3.
DS = dry solid; P = phosphorus; t = tonne; g P/kg DS = grams of phosphorus per kilogram of dry solid.

Solid Waste Collection

Swedish municipalities have a statutory responsibility for the collection and treatment of household waste. There is no equivalent responsibility for industrial waste and its collection and treatment is subject to free competition between municipal as well as other waste management companies. A systematic quantification of phosphorus flows from industry was not possible, as neither the environmental administration of Gothenburg nor the SWTP track the composition of industrial wastes.

The SWTP collected 671,000 t of solid waste in the year 2009. The most important waste categories were combustible household waste (unsorted, also referred to as "residual waste"; 265,000 t), combustible industrial waste (141,000 t), and recyclable solid waste (61,000 t). Households in Gothenburg contributed 142,000 t of combustible waste, while neighboring Swedish municipalities contributed 79,000 t and Norwegian municipalities contributed 44,000 t (Renova AB 2010).

Phosphorus flows from households in Gothenburg were estimated based on the amount of various categories of sorted solid waste disposed of by households (table 2) as well as the composition of residual waste (table 3). A total of 92 t P/yr (<F20*>) is contained in sorted solid waste disposed of by households in Gothenburg. Imported residual waste was assumed to have a similar composition to the waste from Gothenburg: households in neighboring Swedish municipalities contribute 39 t P/yr (<F15>) to the SWTP, while Norwegian household waste accounts for 22 t P/yr (<F14>).

A national study (Jensen et al. 2011) reports waste production factors for separately collected food waste per employee for restaurants (1,059 kg/yr), bakeries (1,900 kg/yr), and charcuteries (2,500 kg/yr), and per portion for municipal kitchens (0.1 kg). The food waste that remains in the residual waste was suggested to be 30%. In addition, in Gothenburg, only 30% of the businesses have access to the separate food waste collection infrastructure. Nineteen million portions were served by municipal kitchens in Gothenburg in 2009 (Mellgren 2010); 8,906 people were employed in restaurants, 460 in charcuteries, and 432 in bakeries (Hakansson 2012). The amount of phosphorus contained in food waste has been estimated to be 29 t P/yr (<F20*>) based on a dryness of 35% and a phosphorus content of 4 g/kg DS (19 t P/yr in residual waste and 10 t P/yr collected separately).

Another estimate of 191 t P/yr[1] (<F33*>) for the total flow of phosphorus from households, businesses, and industry toward the waste-fueled district heating plant (DHP) was made based on a waste composition analysis (see table 4) of the solid

Table 3 Waste fractions of residual waste disposed of by households in Gothenburg, Sweden, 2009[a]

Waste fraction	*Amount (% fresh weight)*	*Amount (t)*	*Dryness (%)*	*P content (g P/kg DS)*	*P content (t P)*
Organic material	30	36,800	35	4	51.6
Paper and cardboard	21	25,800	100	0.24	6.5
Wood	2	2,500	81	0.31	0.6
Textiles	11	13,500	100	0.14	1.9
Glass, metal, and plastic	21	25,800			
Remaining	15	18,400			
Total	100	122,800			60.6

Notes: [a]Porse (2011).
DS = dry solid; P = phosphorus; t = tonne; g P/kg DS = grams of phosphorus per kilogram of dry solid.

Table 4 Waste composition at the district heating plant, 2009

Fraction of incoming waste at the district heating plant	*Amount (% fresh weight)*	*Amount (t)*	*Dryness (%)*	*P content (g/kg DS)*	*P content (t P)*
Domestic residual waste (garbage bags)	32	145,200			60.6[a]
Organic waste	15	68,100	35	4	95.3
Paper and cardboard	18	81,700	100	0.24	19.6
Wood	11	49,900	81	0.31	12.5
Textiles	4	18,200	100	0.14	2.5
Glass, metal, and plastic	14	63,500			
Remaining	6	27,200			
Total	100	453,800			190.5

Notes: [a]Remaining tonnage with unknown P content, based on table 3.
P = phosphorus; g/kg DS = grams per kilogram of dry solids; t P = tonnes of phosphorus.

waste arriving at the DHP (Claesson et al. 2009). It should be mentioned that the composition of the waste at the DHP was determined once in a duplicate sample, but the waste composition may differ substantially throughout the year.

Waste Treatment

Wastewater Treatment

In 2009 two industrial WWTPs, two municipal WWTPs, and 2,091 on-site wastewater treatment facilities (on-site WWTFs) were located within the municipality of Gothenburg. The main municipal WWTP served 649,352 permanent residents, whereas the 1,850 permanent residents of the Southern Gothenburg Archipelago were connected to a minor municipal WWTP.

Sewage sludge from the main WWTP is anaerobically digested at the adjacent biogas plant. The environmental report for the city of Gothenburg provides the following phosphorus emissions from effluents: main WWTP 36 t P/yr (<F42>), minor WWTP 1 t P/yr (<F40>), industrial WWTPs 1 t P/yr (<F48>), on-site WWTFs 3 t P/yr (<F39>), and sewer overflows 4 t P/yr (<F30>) (Göteborg Stad 2010).

The yearly environmental report of the main WWTP provides the following figures: 432 t P/yr (<F31*>) are contained in raw wastewater entering the plant and sludge from grease interceptors in the food industry corresponding to 3 t P/yr (<F32>) was added to the anaerobic digester. Screening containing approximately 4 t P/yr (<F43>) is disposed of at the DHP; the dewatered sludge is, for the most part, used as backfilling soil on construction sites (<F41>) (Gryaab 2010).

Solid Waste Treatment

In 2009, one waste-fueled DHP, one composting plant, and two operational landfills were located within the municipality of Gothenburg. At the DHP, 453,858 t of combustible waste was incinerated. Solid waste to be incinerated at the DHP was sampled once a month over a period of 1 year. The samples were incinerated and the residual ash was analyzed. The median phosphorus concentration was 1.15 g P/kg DS (Claesson et al. 2009). Based on these values and an average dryness of 63.5%, the amount of phosphorus contained in the waste incinerated at the DHP would be on the order of 332 t P/yr (<F33*>). Incineration residues from the DHP are landfilled (<F44>).

At the composting plant, 14,121 t of domestic and commercial food waste as well as 5,666 t of garden and park waste were composted. Based on the respective phosphorus content and dryness for food waste and wood (see table 4), food waste contains 20 t P/yr (<F37*>) and garden waste contains 1 t P/yr (<F37*>). An additional 60,000 t of solid waste with unknown phosphorus content (<F34>) and less than 5% organic content are landfilled without treatment (Renova AB 2010).

Missing Sources and Pathways

Wastewater Pathways

The total output from the WWTP amounts to 374 t P/yr and the total input is 435 t P/yr. The gap of 61 t P/yr indicates missing pathways or inaccurate sampling of phosphorus concentrations. According to the plant's engineer, the measurements of the phosphorus concentration in the incoming wastewater are difficult to obtain and prone to inaccuracy, while measurements of the phosphorus concentration in the sludge and treated wastewater are reasonably accurate (Matsson 2011). The sum of the outputs from the plant is probably closer to the true value. For the municipal sewer system, there is a gap of 8 t P/yr between the input (371 P/yr) and output (379 t P/yr). The infiltration and inflow (other than stormwater), which constitute 45% of the total input to the WWTP with an unknown phosphorus concentration, may account for this difference.

Solid Waste Pathways

As for the amount of phosphorus arriving at the DHP, we believe that the estimate based on 12 samples taken throughout 1 year on a monthly basis is more reliable than the estimate based on one duplicate sample. Therefore we take a flow of 332 t P/yr as a reference value. In order to identify potential missing sources and pathways, we examined the different flows related to the solid waste pathways more closely. The assumed food wasted by households in Gothenburg (75 t P/yr) corresponds well with the amount of food waste discarded (73 t P/yr). Of the 147 t P/yr food waste ending up at the DHP, 25 t P/yr could not be related to a source, but likely is from distribution. To balance the total amount of food waste found in sorted solid waste, we increased the import (<F02>) and disposal (<F20*>) of food commodities to 125 t P/yr. We also increased the net import (<F05>) and disposal (<F20*>) of paper products for Gothenburg to 20 t P/yr, net the import (<F06>) and disposal (<F20*>) of wood products to 12 t P/yr, and the import (<F08>) and disposal (<F20*>) of textile products to 3 t P/yr. Newspaper and paper packaging (3 t P/yr) seems not to be the main source of paper and cardboard, and wooden packages (4 t P/yr) are not the main source of wood products.

Results and Discussion

The results of the phosphorus flow analysis for the city of Gothenburg are presented in figure 2 of this article and Table S1 of the supporting information available on the Journal's Web site. The importation of food commodities produces the largest flow of phosphorus into the city of Gothenburg, and about 50% of the total input of phosphorus is contained in food and beverages. Detergents comprise 6% of the total phosphorus input and pet food 4%, while goods for agriculture make up only 2%. Imports of wastewater and municipal solid waste from outside the city contribute 10% each of the total phosphorus input into the system.

Wastewater and solid waste represent the main flows and sinks: sewage sludge and incineration residues each contain 40% of the total output of phosphorus. This result is in contrast to the common assumption that wastewater contains most of the phosphorus in urban areas. Therefore the potential of solid waste management in the recycling of phosphorus may be underestimated. For example, the Swedish policy for phosphorus recycling relies on the recovery of phosphorus contained in wastewater (Swedish Government 2005).

Due to poor separation of food waste from other waste streams, it contributes a major fraction of phosphorus in incineration residues (see figure 3). In Gothenburg, the separation of biowaste (kitchen and garden waste) began in 1997, and in 2009, 30% of private houses and businesses and 65% of the population in apartment buildings had access to the infrastructure for separate collection of biowaste (Hed 2012). Additionally, 30% of private houses have their own composting bins. Our analysis shows that 20% of food waste from households and businesses is collected separately: 6 t of phosphorus were found in home compost and may have been returned to agriculture and 20 t of phosphorus were composted at the municipal plant and used for horticultural purposes. Since 2011, a major part of separately collected food waste is sent to a biogas plant outside the metropolitan area instead of the composting plant and the resulting residue is recycled to agriculture.

The distribution of urban phosphorus differs significantly from that on national and global scales, where agricultural flows play a major role. In contrast, agricultural flows in Gothenburg are marginal compared to flows related to the urban waste management infrastructure. Also, studies on a global scale suggest that nearly 75% to 90% of phosphorus in urban areas is found in sewage (Brunner 2010; Cordell et al. 2009). However, our result is in line with a study on the EU level where equal per capita phosphorus output was found for sewage sludge and solid waste (Ott and Rechberger 2012). This emphasizes the necessity of estimating resource flows on all scales: global, economy-wide, national, and city.

The pathways of phosphorus through the city of Gothenburg are likely to be common to many other cities with municipal sewage systems and landfilling of incinerated solid waste or direct landfilling. The largest flow of phosphorus toward the incineration facility is food waste. The fraction of discarded biodegradable waste in developed countries is close to 30%, while in developing countries it can amount to up to 80% (UN Habitat 2010). Therefore a potentially even larger amount of phosphorus is buried in landfills in the developing world. In addition, the disposal of sewage sludge to landfills, often via incineration, is also common and further increases accumulation in this sink. The Netherlands incinerates 60% of sewage sludge; Japan, Germany, the United Kingdom, and France incinerate at least 20% of their sludge (Dawson and Hilton 2011; Matsubae-Yokoyama et al. 2009). As a result, a Japanese study showed the flow of phosphorus toward landfills to be a major flow within the waste treatment and environmental sector (Matsubae-Yokoyama et al. 2009).

With current waste management practices, the flows of phosphorus into disposal sinks are expected to increase along with urban population growth. The greatest increase in per capita phosphorus accumulation may happen in developing countries, since increased wealth entails increased waste generation. For example, municipal waste per capita increased by 29% in North America, 35% in Organization for Economic Co-operation and Development (OECD) countries, and 54% in the European Union 15 (EU15) from 1980 to 2005, along with steadily growing gross domestic products (GDPs). In addition, industrial waste is likely to increase at a rate similar to the 66% increase in Sweden between 1993 and 2006.

It has been estimated for Sweden and Finland that 15% to 20% of the phosphorus demand can be met by the content in sewage sludge (Antikainen et al. 2005; Swedish Government 2005). Estimation for the 9,000 t of phosphorus sold as fertilizer in 2009 suggests that 40% of the demand can be met by phosphorus contained in the 926,000 t of incineration residues produced annually with an average 0.4% phosphorus content. In Gothenburg in 2009, 4% of the phosphorus input was recycled to agriculture as manure and 0.3% (1 t phosphorus) as certified sludge. Most of the sludge and compost was used as backfilling soil at construction sites and for horticultural purposes, respectively. In the EU, less than 40% of the sewage sludge is returned to agriculture due to real or perceived contamination by heavy metals (Dawson and Hilton 2011).

Unless urban phosphorus flows can be returned to agriculture, the rate of depletion of rock resources, accompanying emissions, and dispersion of contaminants will increase. Many decisions concerning resource management are made on a city

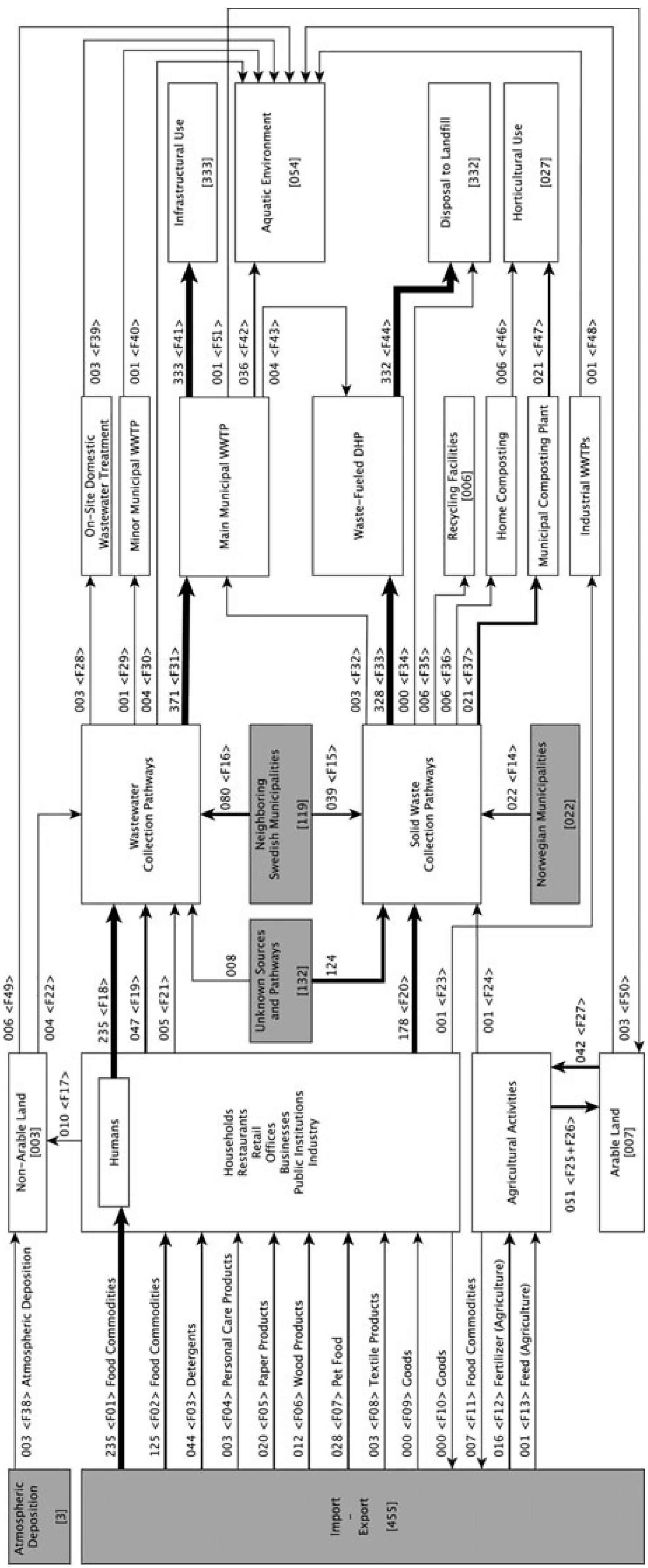

Figure 2 Results of the phosphorus flow analysis for Gothenburg, Sweden, in 2009, in tonnes of phosphorus per year (t P/yr). The thickness of the lines depicts the magnitudes of the flows.

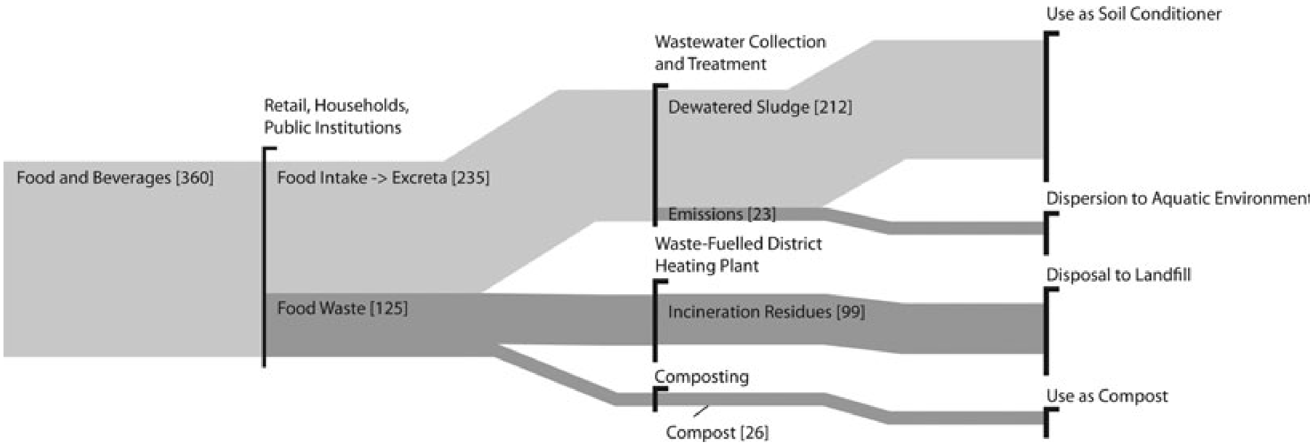

Figure 3 Dispersion pathways for phosphorus contained in food products in Gothenburg, Sweden, in 2009, in tonnes of phosphorus per year (t P/yr).

level, and here we investigate several scenarios for phosphorus management, with Gothenburg as an example.

Scenarios with Alternative Waste Systems in Gothenburg

Five management strategies and their impact on phosphorus flows in Gothenburg have been investigated: (1) incineration of all food waste, (2) separate collection of 70% of food waste from households and businesses, (3) installation of kitchen grinders, (4) urine diversion, and (5) separation of blackwater and food waste. The key difference between the options are the flows of food waste and excreta toward different collection and treatment facilities. For all scenarios, treatment efficiency of the WWTP is assumed to be equal to the current conditions. As suggested by the plant's engineers, treatment efficiency is a fixed percentage and thus is independent of the load (Matsson 2011). The diverted urine, treatment residuals of separately digested food waste, and blackwater with food waste were considered a fertilizing product for agricultural use because, in contrast to sewage sludge, they are not contaminated with heavy metals and persistent organic pollutants originating from stormwater and greywater (Hernandez Leal 2010; Lamprea and Ruban 2008; Vinnerås 2001). Sludge from the WWTP was assigned its current use as a backfilling soil.

The scenario of incinerating all food waste is closest to the current system (figure 4). This is due to the fact that only a small fraction of food waste is currently separated from other waste streams in Gothenburg. This scenario is not desirable for maximizing the reuse of phosphorus as fertilizer. Even if uncontaminated phosphorus could be recovered from incineration ash, it would still need to be combined with nitrogen, potassium, and micronutrients to form a stoichiometrically balanced fertilizer product.

The current strategy of the city is to improve the separate collection of food waste for subsequent digestion and use of the resulting residue in agriculture. When separation of 70% of the food waste from households and businesses is assumed, a total of 88 t P/yr will be collected and returned to agriculture (figure 4).

The scenario of urine diversion has similar potential. While urine constitutes no more than 1% of the total volume of wastewater, it contains 50% of the phosphorus (Vinnerås and Jonsson 2002). The diverted stream would contain 82 t P/yr if 70% collection is assumed (Vinnerås and Jonsson 2002). The decreased nutrient load to the centralized WWTP would result in a reduction of emissions to the aquatic environment of 10 t P/yr. The content of bioavailable nutrients in urine is closest to the content in mineral fertilizers, and crop yields become identical when treated with mineral fertilizer or urine (Peter-Frölich et al. 2007). Urine is almost free of heavy metals and pathogens and is easily sanitized by storage (Kvarnström et al. 2006), ozone, or ultraviolet (UV) light. Human urine contains ingested pharmaceuticals and hormones, though in much lower concentrations than animal manure, which is already used as a crop fertilizer (Lienert et al. 2007; Winker 2010).

The benefits of introducing sink-mounted kitchen grinders in Stockholm and Gothenburg are being discussed by city councils. The technology is implemented in centralized wastewater systems in North America, Japan, and Australia. Kitchen grinders simplify the separation process and separation of 80 weight percent (wt%) of food waste has been achieved in a pilot project in Gothenburg (Karlsson et al. 2008). This would result in an additional 72 t P/yr in the sludge and an increase of emissions to the aquatic environment of 7 t P/yr. However, no increase in the recycling of nutrients to agriculture is expected in this case, as the sludge would probably still be perceived as contaminated.

Blackwater and food waste separation would enable the most complete recycling of nutrients, with a transfer of 245 t P/yr back to agriculture. Eighty percent of the phosphorus contained in blackwater mixed with ground food is plant-available phosphates (Karlsson et al. 2008). A blackwater stream would contain few pollutants, as its main sources are domestic greywater and urban stormwater, and the addition of urea or ammonia reduces pathogens in blackwater (Winker et al. 2009). Emissions

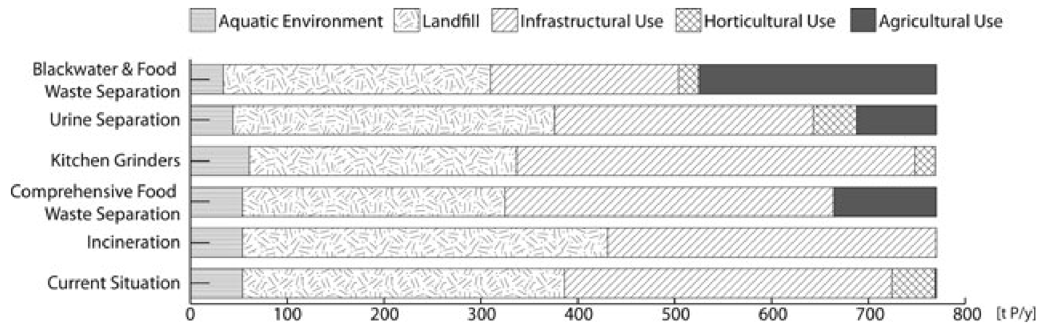

Figure 4 Output pathways for phosphorus for the current system and the alternative scenarios.

to the aquatic environment will decrease by 20 t P/yr due to the reduction in nutrient load.

Conclusion

The major phosphorus flows are connected to food consumption and phosphorus is accumulated in two sinks: deposits of sewage sludge and incineration ash. About 40% of the total output of phosphorus in Gothenburg is found in each of these sinks.

Because solid waste was found to be an equally important sink for phosphorus, a focus on wastewater as an option for recycling urban phosphorus is not sufficient. The Swedish environmental goal of applying 60% of the phosphorus contained in wastewater on productive land targets only 30% of the total phosphorus available for recycling in the city of Gothenburg. The role of solid waste in nutrient management should be reconsidered and more whole system–oriented routes for sustainable disposal of biowaste assessed.

We showed that phosphorus flows differ significantly on a city scale compared to national and global scales, where agricultural flows play a major role. In contrast, agricultural flows in Gothenburg are marginal compared to flows related to the urban waste management infrastructure.

Urban sinks contain 90% of the phosphorus budget of the city, while less than 0.1% is currently returned to agriculture and 6% to horticulture. The rest is dissipated through infrastructural use of sewage sludge and is being accumulated in landfills.

Five management strategies for urban waste were analyzed from the perspective of phosphorus flows. The results suggest that the current situation, which is close to the scenario of incineration of all food waste, results in phosphorus-containing material of the lowest agricultural quality. Incineration removes nitrogen and carbon from biowaste, resulting in an unknown recycling potential of the incineration residue. The introduction of kitchen grinders will increase the collection of food waste, but improved sludge quality and public acceptance is required to enable phosphorus recycling. Separate treatment of blackwater and food waste could result in the most complete recycling of phosphorus; however, it is also the scenario farthest from the current reality. Urine separation may be a valid compromise. Separate collection and digestion of 70% of both household and commercial food waste would return 15% of the recycling potential to agriculture. The remaining 85% in sewage sludge and incineration ash should be addressed.

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Notes

1. The term tonne refers to metric ton. One tonne (t) = 10^3 kilograms (kg, SI) ≈ 1.1 short tons.
2. One kilogram (kg, SI) ≈ 2.204 pounds (lb).
3. One gram (g) = 10^{-3} kilograms (kg, SI) ≈ 0.035 ounces (oz).
4. One milligram (mg, SI) = 10^{-3} grams (g) ≈ 3.53×10^{-5} ounces (oz). One square meter (m^2, SI) ≈ 10.76 square feet (ft^2).

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Supporting Information

Additional supporting information may be found in the online version of this article.

Supporting Information S1: This supporting information provides a table detailing metadata and calculations used in the study.