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REPORT

Phosphorus Flows to and from Swedish Agriculture and Food Chain

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Abstract Phosphorus flows in Swedish agriculture and food chain were studied by material flow analysis. The system studied included agriculture, food consumption, related waste and wastewater from private households and municipal wastewater treatment plants. Swedish farmland had net annual phosphorus inputs of $\sim$12 600 metric tons (4.1 kg P ha^{-1}) in 2008–2010. The total import of phosphorus in food and feed to Sweden exceed imports of phosphorus in fertilizers. Despite strict animal density regulations relating to manure phosphorus content, phosphorus is accumulating on Swedish animal farms. The total quantity of manure produced greatly exceeds imported mineral phosphorus fertilizer and almost equals total phosphorus inputs to Swedish farmland.

Keywords Fertilizer · Manure · Material flow analysis · Sewage sludge · Waste · Wastewater

INTRODUCTION

Sustainable food production requires sustainable access to phosphorus, which is indispensable and irreplaceable in plant cultivation. Animals and humans also need phosphorus to grow and survive. Phosphorus is an element that cannot disappear but can be dispersed, and is thereby difficult to reuse. Reserves of mineable phosphorus rock are limited, with a horizon of 50–100 years suggested most frequently (Cordell et al. 2009). The type of rock worth mining is also debated (IFDC 2011; Global Phosphorus Network 2011). As phosphorus reserves are limited careful management is important, but information on phosphorus flows in society is lacking.

Phosphorus is often associated with the toxic heavy metal cadmium, dietary intake of which poses a threat to human health (Suwazono et al. 2006; EFSA CONTAM 2009). Food, especially vegetable foods, is the main source of cadmium for the non-smoking population. Cadmium is taken up by plants and the cadmium content can increase with increased nitrogen fertilization (Wangstrand et al. 2007). Phosphorus fertilizers add cadmium to soils, in amounts ranging between 0.2 and 860 mg Cd kg^{-1} P (Oosterhuis et al. 2000). Sweden has national regulations on cadmium content in commercial fertilizers and those sold in Sweden contain on average 5.6 mg Cd kg^{-1} P, equal to 2.4 mg Cd kg^{-1} P_2O_5 (Statistics Sweden 2011a). However, only about 13 % of world resources comprise phosphate rock with low cadmium content (Oosterhuis et al. 2000; Swedish EPA 2010). Cadmium can be removed while producing the fertilizer but this is rarely done as the cost is about 0.7 USD per kg P (Bertilsson 2011). Thus, to limit net imports of cadmium to the food chain, it is important to recycle phosphorus.

Natural recycling of nutrients from human excreta ended with the water closet and urbanization and the nutrients became a problem for surface waters because of eutrophication. In 1955, only one Swedish city out of four had wastewater treatment (Augustinsson 2003). Problems with hygiene and eutrophication resulted in obligatory wastewater treatment in 1969 (Swedish Code of Statutes 1969; Drangert et al. 2002), at which time phosphorus in wastewater was seen as a problem, not a resource.

The Brundtland Commission placed sustainability on the political agenda (WCED 1987). In Sweden, attention turned to reuse and recycling and in 1990, the Swedish Environmental Protection Agency (EPA) was given a Government commission entitled *Cleaner Sludge*. A pioneer nutrient flow balance for Swedish agriculture and the Swedish food chain was drawn up, but the only inputs included in the analysis were mineral fertilizer and detergents (Pettersson 1992). Efforts have since been made to estimate historical and present-day regional phosphorus flows in the food and feed chain (Neset et al. 2008), but up-to-date figures on phosphorus flows on national level are still lacking. This study sought to redress this by analyzing current flows of phosphorus in the food chain, including wastewater and agricultural waste, in Sweden.

This study originally sought to analyze current phosphorus and cadmium flows in Swedish agriculture and food chain, including wastewater and agricultural waste but this proved impossible for cadmium due to lack of data. The only updated documented cadmium flows of relevance were those in mineral fertilizer (55 kg year^{-1}), atmospheric deposition (1200 kg year^{-1}), sewage sludge (170 kg year^{-1}) and emissions to water from WWTP (50 kg year^{-1}) (Statistics Sweden 2010a, 2011c; KEMI 2011).

METHOD

Flows of phosphorus in the Swedish food chain, including agriculture, were quantified on a yearly basis by material flow analysis (MFA), sometimes called substance flow analysis (SFA), according to methodology described by Brunner and Rechberger (2004). The analysis was based on an inventory of inputs and outputs of the system and important internal flows. The system studied was food production and food consumption in Sweden, including the food chain and related waste and wastewater treatment. Thus, other phosphorus flows to wastewater or waste, such as phosphorus in laundry and dishwashing detergents, were also included in the system.

Phosphorus inputs to Swedish agriculture comprise phosphorus in all supplies used in agriculture, e.g. fertilizers, feed minerals and imported animal feedstuffs. In addition, atmospheric deposition of phosphorus makes a direct input to arable land. Imports of food and commodities for food processing from other countries were also accounted for as inputs to the system studied. Phosphorus in products and wastes used or recycled within agriculture (e.g. fodder, manure) does not pass outside the system boundaries, and thus does not affect the national balance.

Phosphorus outputs from the system comprise phosphorus in exported agricultural products and phosphorus in waste and wastewater that is not reused as fodder or fertilizer in agriculture, but leaves the system as emissions to the environment or waste. Field-scale phosphorus losses through erosion and leakage to water bodies were also included. Most activities in the studied system have a rapid turnover of phosphorous, why the changes in stocks of phosphorous in these have not been investigated. The agricultural soil, however, represents a significant stock of phosphorous with a rather slow turnover, why the collected data were used to calculate the phosphorous balance on arable land, i.e. the change in phosphorous stock in cultivated soil per year.

Official statistics for the period 2008–2010 were used where possible. For flows that fluctuate annually, calculations were based on an average for 2–3 years. When official data were lacking, information was collected from scientific papers, databases, authorities or companies. Because of the recent Swedish regulation on phosphates in certain detergents, the data were corrected to reflect the current situation. The calculations were based on a total acreage of 3 079 700 ha, i.e. total arable acreage in Sweden, including pasture in 2009 (Swedish Board of Agriculture 2010e). One reason to include pasture is that significant portions of phosphorus flows go via milk and meat. An uncertainty analysis was made according to a method presented by Hedbrant and Sörme (2001). Uncertainty factors were estimated due to origin of data and the uncertainty interval was calculated by multiplying and dividing the data with the factors.

RESULTS OF INVENTORY

Inventory results for the phosphorus inputs, internal flows and outputs from the system studied, Swedish agriculture and food chain, are presented in Table 1 and discussed below. Figure 1 shows phosphorus inputs and outputs and flows inside the system boundaries.

Inputs

Mineral Fertilizers

When World War II ended, many Swedish soils had low phosphorus content and produced low yields. Phosphorus imports in mineral fertilizer increased thereafter and peaked in 1973–1974 at 70 000 tons,[1] corresponding to 24 kg ha^{-1} arable land (Statistics Sweden 1995). The increased mineral fertilization increased the average soil phosphorus content with ~700 kg ha^{-1} in 1950–1990 (Andersson et al. 1998) and yields increased. Today, many soils have satisfactory phosphorus status. Furthermore, the phosphorus content in manure was not always valued and accounted for in the 1970s–1980s (G. Bertilsson, personal communication 2011), but today is regarded as having the same fertilizer value as mineral fertilizer (Swedish Board of Agriculture 2010d).

[1] Throughout the text ton refers to metric ton = 1000 kg.

Table 1 Inputs, outputs and balance of phosphorus (tons year^{-1}and kg ha^{-1}) for Swedish agriculture and the food chain

	P (kg ha^{-1})	P (tons year^{-1})	Sources	Uncertainty factor
Input				
Mineral fertilizers	3.5	10 800	1	1.1
Other fertilizers	0.3	860	2, 3	1.3
Imported fodder	1.8	5600	4, 5, 6, 7, 8	1.3
Feed minerals	0.9	2700	9	1.3
Live animals		4	10, 11	1.3
Atmospheric deposition	0.3	924	11, 12, 13	3
Import food excl. fish etc.	1.9	5760	8, 11, 14, 15, 16	1.5
Fish, seafood, game animals etc.	0.1	300	14, 15, 17	2
Other sources to wastewater	0.2	575	18, 19, 20	2
Total inputs	*8.9*	*27 523*		
Output				
Export food incl. cereals	1.8	5560	8, 11, 14, 15, 16	1.5
Losses from arable land	0.3	924	12, 13	1.3
Household food waste	0.4	1320	21	1.5
Food industry, waste, pet food	0.5	1550	2, 21, 22	1.5
Ethanol production, export of by-product	0.2	540	23	1.3
Emissions from private sewages	0.2	620	11, 19, 20, 24	2
Emissions WWTPs	0.1	285	25	1.5
Sludge to non agricultural use	1.3	4095	25	1.3
Total exports and losses	*4.8*	*14 894*		
Balance (net input)	*4.1*	*12 629*		
Uncertainty range	*(3.6–5.0)*	*(11 000–15 500)*		

The calculated probable value was multiplied or divided by the uncertainty factor (Hedbrant and Sörme 2001)

[1] Statistics Sweden (2011a), [2] P.-J. Lööf, personal communication (2011), [3] E. Olsson, personal communication (2011), [4] SLU (2011a), [5] R. Spörndly, personal communication (2011), [6] Swedish Board of Agriculture (2009), [7] Swedish Board of Agriculture (2010a), [8] Statistics Sweden (2011b), [9] S.O. Malmqvist, personal communication (2011), [10] Swedish Board of Agriculture (2010b), [11] Steineck et al. (2000), [12] Swedish Board of Agriculture (2008), [13] Statistics Sweden (2011c), [14] Tiessen (1995), [15] National Food Agency (2011), [16] USDA (2011), [17] Swedish Board of Agriculture (2010c), [18] Statistics Sweden (2010b), [19] Vinnerås (2002), [20] Swedish EPA (2006), [21] Wivstad et al. (2009), [22] L. Virto, personal communication (2011), [23] B. Bäckman, personal communication (2011), [24] Swedish EPA (2012), [25] Statistics Sweden (2010a)

As a result, Swedish fertilization recommendations have changed (Swedish Board of Agriculture 2010d). In recent decades, the use of phosphorus mineral fertilizer has declined in terms of total amount and per hectare. Average imports of mineral phosphorus fertilizer were ~10 800 tons (Statistics Sweden 2011a).

Other Fertilizers

In 2009, about 360 000 ha in Sweden were organically farmed (Swedish Board of Agriculture 2010e). Organic production does not permit mineral fertilizers, but still needs phosphorus. Domestic sources such as manure are mainly used, but import of organic phosphorus also occurs, mainly as meat-and-bone meal, in which form ~860 tons phosphorus year^{-1} were imported in 2008 and 2009 (P.-J. Lööf, personal communication 2011; E. Olsson, personal communication 2011).

Imported Feedstuffs and Live Animals

Most roughage and grain required for animal production is produced inside Sweden, but many concentrates and minerals are imported. To calculate the phosphorus imports in feedstuffs an average of two separate data sources were used here, from the Swedish Board of Agriculture and Statistics Sweden. National data on imports are expressed in tons, with no information on water or phosphorus content. To calculate the dry matter (DM) and phosphorus content, we used information from feed tables published by SLU (2011a) and expert judgment (R. Spörndly, personal communication 2011).

All companies importing feedstuffs provide data to the Swedish Board of Agriculture, which checks the quality and hygiene of the feed (Swedish Board of Agriculture 2009, 2010a). Within these data, feed to animals in agriculture and horses is distinguished from feed to other animals such as pets, animals for fur production and wild birds. All manure

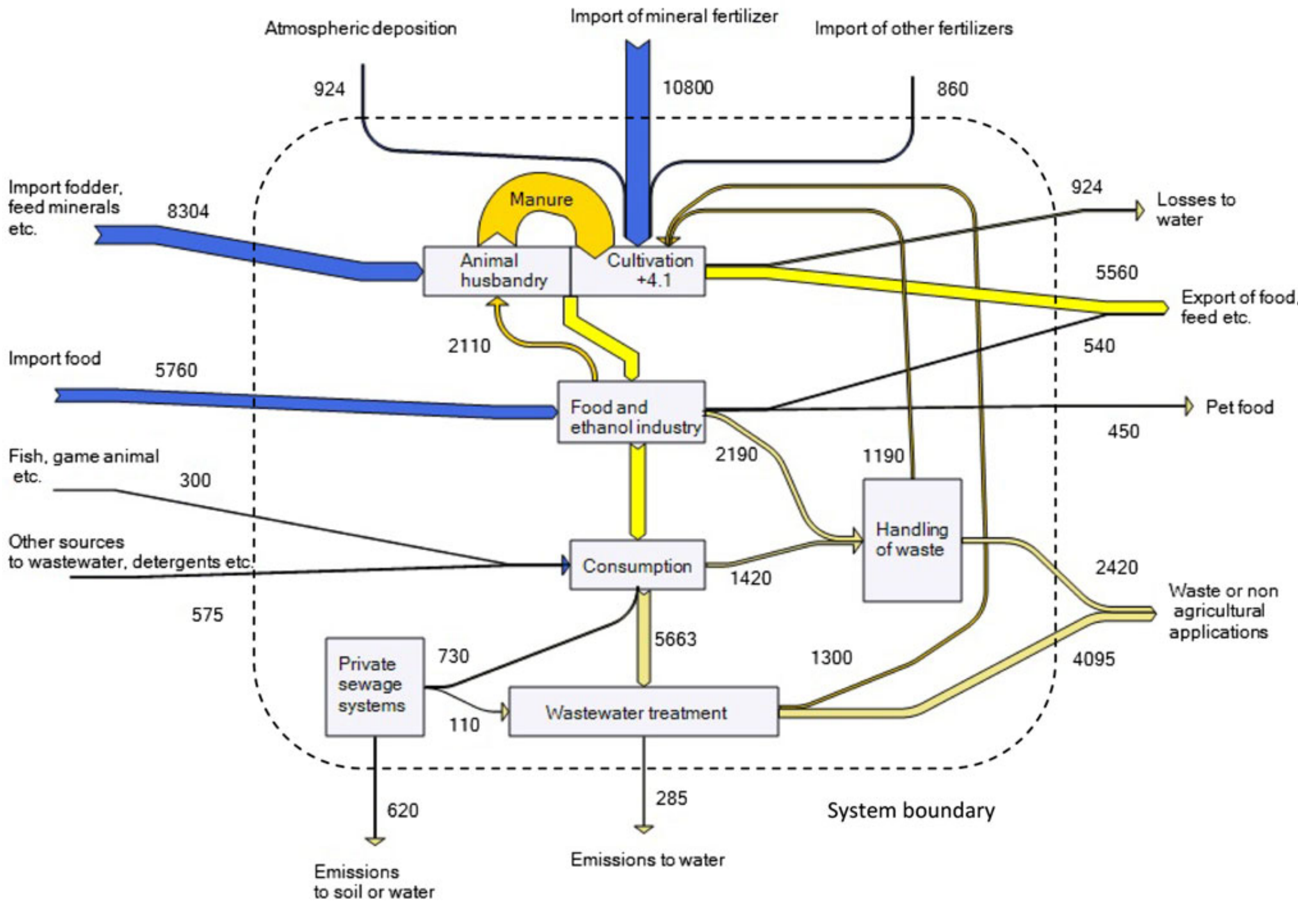

Fig. 1 Quantified flows in tons of phosphorus in Swedish agriculture and the food chain. *Boxes* The processes of cultivation, consumption, treatment etc. Stock change in soil is shown in kg ha $^{-1}$. The width of the arrow corresponds to the size of the flow of phosphorus. When corresponding value is lacking for an arrow the flow is only indirectly calculated from other results in this study

from agricultural animals and horses was assumed to be used on farmland. Furthermore, it was assumed that 50 % of the phosphorus to 'other animals' was used for animals kept for fur production and that their manure was used on farmland. The other 50 % used for 'other animals' was assumed to go to pets and birds and their manure was assumed to not enter the wastewater system or agricultural land. This inflow was thus excluded from the flow analysis. Calculations of average annual imports of phosphorus in farm animal feedstuffs were based on data from 2008 to 2009. Some farmers import feeds directly and these quantities are not included in statistics, but were assumed to be negligible. The resulting average annual import of phosphorus was almost 5300 tons, according to data from the Swedish Board of Agriculture.

Independently, Statistics Sweden collects data on feed imports (Statistics Sweden 2011b). These data originate from Swedish customs for trade outside the EU and from companies for trade within the EU. Companies that import and export goods to a value of below 660 000 USD (4.5 million Swedish kronor) within the EU are not obliged to report their trade statistics. Unreported imports are adjusted for by Statistics Sweden, but are probably underestimated for some goods and countries (M. Adolfsson, personal communication 2011). In addition, cereals for feed are not included as they are reported together with data on cereals for food purposes. Despite this, the data on feed imports from Statistics Sweden give annual phosphorus imports of 5900 tons, which is about 12 % higher than the figure from the Swedish Board of Agriculture.

In the study, we used the mean value of these two datasets (5600 tons) for imports of phosphorus in feed (Table 1). A small amount of phosphorus (about 4 tons) is imported with 645 tons live animals, mainly poultry (Swedish Board of Agriculture 2010b).

Feed Minerals

Animal feed minerals are produced in Sweden by one company. The raw material, phosphoric acid, is imported. About 2700 tons phosphorus year^{-1} are used as animal feed minerals or feed phosphates (S.-O. Malmqvist, personal communication 2011).

Atmospheric Deposition

The most commonly used value for atmospheric deposition of phosphorus is 0.3 kg ha^{-1}, which is based on earlier measurements (Steineck et al. 2000; Swedish Board of Agriculture 2008; Statistics Sweden 2011c). Official monitoring of phosphorus deposition in Sweden ceased at the beginning of the 1990s due to low concentrations and difficulties in collecting and evaluating samples. Contamination from bird droppings, soil dust, organic particles falling from trees and human disturbances were some of the problems. During the 1990s, three monitoring stations in different parts of Sweden recorded annual phosphorus deposition of 0.05, 0.24 and 0.97 kg ha^{-1}, respectively (Knulst 2001). Although associated with great uncertainty, a value of 0.3 kg ha^{-1} was used in this study, resulting in 924 tons phosphorus in total to agricultural land. However, the deposition could be much lower. In the Fifth Baltic Sea Pollution Load Compilation (PLC 5) to the Helsinki Commission (HELCOM), Sweden used a value of 0.04 kg phosphorus ha^{-1} based on data from 19 stations in 2006 (Swedish EPA 2009).

Food Excluding Fish and Seafood

Food production in Sweden has decreased and imports have increased in recent decades (Swedish Board of Agriculture 2010b). As a consequence, imported food has become a considerable phosphorus inflow to Sweden. Information about the volume of food imports (Statistics Sweden 2011b) was combined with information on DM content and phosphorus content from databases and the literature (Tiessen 1995; Steineck et al. 2000; National Food Agency 2011; USDA 2011), resulting in total imports of 5760 tons phosphorus $year^{-1}$ (Table 1). Cereals to feed and food represented the largest fraction of imports (1540 tons), while dairy products and eggs represented ~700 tons. Fish was calculated separately, as explained below. Hides, skins and tobacco included in the statistics were excluded, as these products were assumed to end up as incinerated waste.

Fish, Seafood, Game and Reindeer

One could assume that all imported fish is consumed in Sweden, resulting in the phosphorus ending up in wastewater. Consequently, exports of fish would not affect the phosphorus balance for agriculture, as the origin is water and not land. However, the picture is more complicated. Much imported fish is salmon from Norway, which is not consumed in Sweden but exported to a third country (Swedish Board of Agriculture 2010b). Data from Statistics Sweden show that imports of fish and seafood approximately equaled exports in 2008 and 2009. The phosphorus in fish and seafood imports and exports was about 950 tons $year^{-1}$. Fish and seafood can also be of domestic origin, caught in the wild or farmed, which is an import to the studied system. This study therefore included consumption of fish and seafood, which in 2008 was about 140 000 tons fresh weight (Swedish Board of Agriculture 2010c). This was assumed to contain 1.9 kg phosphorus ton^{-1} fresh weight (National Food Agency 2011).

Phosphorus in meat from game animals and reindeer was regarded here as an input to the studied system, as they graze in the wild, outside the system boundaries determined as agricultural land. Exceptions occur in that game animals can graze on farmland and reindeer are sometimes fed with agricultural products. The associated phosphorus flows were assumed to be negligible. Total consumption of game animals and reindeer meat was calculated from consumption data from the Swedish Board of Agriculture (2010c) and data on phosphorus content (Tiessen 1995).

Altogether, this gave phosphorus inputs to the sewage system from consumption of fish, seafood, game animals and reindeer of about 300 tons $year^{-1}$.

Other Sources to Wastewater

Phosphorus in detergents and other substances used in households and food industry interfere with phosphorus in the food chain, as the flows are mixed in the wastewater system. In Sweden, only wastewater with a composition similar to household wastewater is allowed to municipal WWTPs (SWWA 2011). Sweden introduced a national regulation on marketing and supply of laundry detergents containing phosphates to consumers for private use in March 2008 and a corresponding regulation for dishwasher detergents was introduced in 2011 (KEMI 2010). This means that statistics for 2008–2010 do not represent the current situation, so an attempt was made to quantify the phosphorus flows after implementation of these regulations.

According to the Swedish Chemicals Agency, annual use of phosphates in detergents for washing and dishwashing was about 6000 tons before the regulation (KEMI 2006). The content of phosphorus in the detergents used was not clear. Instead, the phosphorus contribution with detergents and other chemicals in households was calculated with measured values from scientific work and authorities. Each person produces on average 0.52 g phosphorus day^{-1} in greywater (water from washing, dishwashing and showering in households) (Vinnerås 2002). About 0.35 g $person^{-1}$ day^{-1} is assumed to come from phosphates in detergents (Swedish EPA 2006). With a population in 2008 of 9.25 million (Statistics Sweden 2010b), this gives estimated inputs of phosphorus to the sewage system of about 575 tons after the regulation on phosphate. In 2009, the content of phosphates in detergents used was around 3000 tons (KEMI 2010), corresponding to phosphorus in an amount close to 575 tons.

Internal Flows and Output

The flows that are outputs and/or internal to the system are summarized in Table 1 and described below. Some processes result in both outputs from the system and internal flows. The latter displays in Tables 2, 3 and Fig. 1.

Export of Agricultural Products

Information about exports of products from agriculture (Statistics Sweden 2011b) was combined with information on DM content and phosphorus content from databases and the literature (Tiessen 1995; Steineck et al. 2000; USDA 2011; National Food Agency 2011). The main exports of Swedish agricultural products are cereals and cereal-based goods. With these exports, almost 3900 tons phosphorus leave the country. Total exports of phosphorus with products from agriculture are 5560 tons year^{-1}.

Losses from Arable Land

Some phosphorus is lost as direct emissions from farmland. This has been measured on experimental fields since 1972 (SLU 2011b). Losses of phosphorus to waters are in the range 0.1–1.8 kg ha^{-1} (Swedish Board of Agriculture 2008), with the differences mainly relating to soil type and topography. Losses of phosphorus from the soil surface are higher in northern Sweden, as the soil is often frozen during snowmelt, which means that the water runs on top of the soil. A typical characteristic of phosphorus losses is that they occur during a very short period (Swedish Board of Agriculture 2008). On average the losses are 0.3 kg ha^{-1} (Swedish Board of Agriculture 2008; Statistics Sweden 2011c), resulting in total losses of 924 tons phosphorus.

Household Food Waste

Household waste analyses show that the average single-family home produces almost 100 kg of food waste per person and year. The majority of household waste is incinerated with energy recovery. If the recyclable material is excluded, about 80 % is incinerated and 20 % is biologically treated (Swedish Waste Management 2011). A study on annual nutrient flows in waste in Sweden found

Table 2 Phosphorus (tons year^{-1}) in waste and other outputs from agricultural products

Source of waste	P content (tons year^{-1})	Used as fertilizer (tons year^{-1})	Used as fodder in Sweden (tons year^{-1})	Output (tons year^{-1})
Household food waste	1420	100	–	1320
Food industry waste, pet food and risk material	4010	1090	1370	1550
Ethanol production, by-product	1280	Occasionally	740	540

Sources: Wivstad et al. (2009), P.-J. Lööf, personal communication (2011), L. Virta, personal communication (2011), B. Bäckman, personal communication (2011)

Table 3 Phosphorus flows (tons year^{-1}) from wastewater after the regulation on phosphates in detergents

	Internal flows			Output flows			Total output
	WWTP > 2000 persons	WWTP < 2000 persons	Private sewage systems	WWTP > 2000 persons	WWTP < 2000 persons	Private sewage systems	
Wastewater	5288	375	730				
Emissions to soil/water						620	620
Emission to water				270	15		285
Sludge	5020	360	110				
Use in cultivation	1300						
Waste or non agricultural use				3720	375		4095
Total output from the system studied, i.e. Swedish agriculture and food chain							5000

WWTP wastewater treatment plant

Sources: Vinnerås (2002), Swedish EPA (2006), Swedish EPA (2012), Statistics Sweden (2010a), Steineck et al. (2000)

that food waste from households contains about 1420 tons phosphorus but only 100 tons are used as fertilizer (Wivstad et al. 2009).

Food Industry Waste, Pet Food and Risk Material

Most of the phosphorus in waste from food processing industries such as breweries, slaughterhouses, dairies, sugar mills, etc. is used either as fertilizer or feed, including pet food (Wivstad et al. 2009; P.-J. Lööf, personal communication 2011). Pet food is defined as a flow exiting the system, as pet manure does not end up on farmland or in wastewater. About 550 tons phosphorus leave the system, 100 tons in waste and 450 tons in pet food. Some phosphorus ends up in waste considered to pose a risk of pathogen spread, defined as 'Category 1 material' in the EU (European Parliament and the Council 2002). Fallen animals and Category 1 material from slaughterhouses are not included in the figures above. This risk material is treated and used as a fuel called Biomal, and has a total phosphorus content of about 1000 tons year^{-1} (L. Virto, personal communication 2011). Altogether, this means that 1550 tons phosphorus leave the system as food industry waste, pet food and risk material (Tables 1, 2).

Ethanol Production, By-product

Sweden has one large-scale producer of grain-based fuel ethanol. A by-product of ethanol production is a protein feed (Agrodrank), which is also used as fertilizer occasionally. In 2008–2009, about 158 000 tons Agrodrank were produced, of which 40–45 % was exported. The DM content is 90 % and the phosphorus content 0.9 % on a DM basis, so about 540 tons phosphorus is exported with Agrodrank every year (B. Bäckman, personal communication 2011).

Wastewater

Emissions of phosphorus to waters from Swedish wastewater treatment plants (WWTP) amounted to 313 tons and the sludge contained 5930 tons phosphorus in 2008, according to national statistics. These statistics do not include WWTP built for <2000 persons, which treat 5–10 % of total wastewater and produce about 415 tons phosphorus in sludge. Losses from the pipe system are also excluded (Statistics Sweden 2010a). As a result of the regulation on phosphates in detergents, there will be a reduction in phosphorus entering wastewater of about 0.35 g person^{-1} day^{-1} (Swedish EPA 2006). This study therefore included a total decline in phosphorus of 1180 tons year^{-1}, of which 87 % will occur in WWTP and 13 % in private sewage systems. About 1.2 million people in Sweden have private sewage systems and 290 000 summer cottages are not connected to municipal WWTP (Swedish EPA 2012). A minor part of the sewage is collected and ends up in a WWTP but most, 80–90 %, is infiltrated into soil, with a possible risk of polluting surface waters or groundwater (Steineck et al. 2000).

Of the phosphorus entering WWTP, 95 % ends up in sewage sludge. The regulation on phosphates will possibly also reduce emissions of phosphorus to waters. Altogether, this gives a figure for phosphorus in sludge of almost 5400 tons year^{-1} after the regulation on phosphates, of which 360 tons year^{-1} come from small WWTP. In 2008, 72 % of the sludge produced in WWTP according to the statistics fulfilled the legal requirements for use on agricultural land, but only 26 % was used in this way (Statistics Sweden 2010a). Due to the costly process required to get sewage sludge certified as fertilizer, this study assumed no use of sludge from small WWTP in agriculture. Altogether, this means that about 5000 tons phosphorus leave the system as emissions to soil or water or as waste or non-agricultural use (Tables 1, 3).

Manure

Manure is circulated in the agricultural system and therefore does not affect the phosphorus balance for Sweden. However, the figures are interesting for comparison with other phosphorus flows and in further calculations. The amount of phosphorus in manure was 25 080 tons in 2009, including 7440 tons phosphorus left on grazing land by animals (Statistics Sweden 2011c), which means that 17 640 tons phosphorus in manure were spread actively on fields by machinery.

DISCUSSION

Increasing Imports of Phosphorus in Food and Feed

The total import of food and feed is now the main contributor to phosphorus inputs in the system studied here (Table 1). Even without imports of mineral and other fertilizers, Sweden has a small positive phosphorus balance on agricultural land. This may indicate that arable land has declined or is not used optimally. Official statistics cite both these reasons. The arable acreage decreased by about 1 % from 2003 to 2010 (Statistics Sweden 2011b). The average cereal crop removes 17 kg phosphorus ha^{-1} and a high-yielding crop can remove 22 kg ha^{-1}, but the average phosphorus outflow is around 11 kg ha^{-1} (Statistics Sweden 2011c). The statistics include all farmland, including pasture. However, even calculating the outflow from the entire agricultural sector per hectare arable land excluding pasture, the phosphorus outflow was only 13 kg ha^{-1} in 2007 (Statistics Sweden 2011b).

Statistics on self-sufficiency in food also confirm decreased production. According to official statistics, self-sufficiency of meat in Sweden decreased from 88 % in 2001 to 82 % in 2003 and that for cheese from 85 to 81 % in the same period (Swedish Board of Agriculture 2003, 2007). The present situation is unknown, as official statistics on this issue are not published since 2003. According to the Swedish Farmers' Federation, almost half the food consumed in Sweden in 2008 was imported (LRF 2010). In Finland, a country with similar conditions for agriculture, self-sufficiency in milk and meat is around 100 % (Statistics Finland 2011). Sweden can be self-sufficient in staple foods and animal feed if agricultural land is used optimally (Larsson 2004), but this is not the case at present.

Is the Phosphorus Surplus Sufficient for Efficient Production?

In this study, net inputs of phosphorus in Sweden were around 12 600 tons or on average 4.1 kg ha^{-1}, for the total area of agricultural land, including pasture (Table 1). The Swedish Board of Agriculture recommends balanced phosphorus fertilization, i.e. only replacing harvested phosphorus, on soils with satisfactory status. Poorer soils need more phosphorus and phosphorus-rich soils may need none at all. Swedish environmental monitoring data show that 34 % of arable soils have good/surplus phosphorus content, 37 % satisfactory content and 29 % low or very low content (Eriksson et al. 2010). Thus, the area needing above-balance phosphorus fertilization is less than the phosphorus-rich area, which can deliver yields with reduced phosphorus fertilization. If available phosphorus sources were used according to recommendations, in theory no imports of mineral fertilizer would be needed.

Phosphorus Balance on Arable Land

Sweden has a moderate phosphorus surplus compared with other European countries. In 1989, net phosphorus fertilization (total fertilization minus crop removal) in Europe ranged from 1 to 60 kg ha^{-1}. Iceland had the lowest value, followed by Sweden, while the Netherlands had the highest. The European and EC 12 average was around 15 kg ha^{-1} (Tiessen 1995). Similar values were reported for 1990–1992 and generally lower for 2002–2004 (OECD 2007) and 2008 (Eurostat 2011b) (Table 4). The figures are not directly comparable to those presented here, as the system boundaries are different, but illustrate differences between countries. The official figure for Sweden in 2008 was 1 kg phosphorus ha^{-1}, but in this study it was 4 kg ha^{-1}. The reason to the difference is not clear as

Table 4 Balance of phosphorus on farmland (inputs–outputs) (kg P ha^{-1})

Year	1990–1992	2002–2004	2008
Sweden	5	2	1
Norway	15	13	15
Finland	20	8	5
Denmark	17	11	7
France	13	4	
Germany	16	4	
The Netherlands	38	19	10
EU 15	18	10	
Canada	1	1	
USA	3	3	
Japan	65	51	
OECD	16	10	

(OECD 2007; OECD 2008)
(Eurostat 2011b)

calculations made by Statistics Sweden are not official and has not been possible to verify. The opposite situation was found in an inventory from Finland, with net phosphorus input of 5 kg ha^{-1} around the year 2000 (Antikainen et al. 2008), while the official statistics gave the figure of 8 kg ha^{-1} (OECD 2008; Eurostat 2011b).

These calculations were based on Sweden as a whole. In discussions of national phosphorus balance, it is important that the phosphorus be optimally balanced nation wide. However, surplus phosphorus is currently concentrated on farms with >0.6 animal unit ha^{-1} (1 animal unit = manure from one cow, three sows or 100 poultry) (Fig. 2). This unbalanced use of phosphorus probably results from the trend towards larger units (conventional and organic) with higher livestock density (LD), i.e. more animal manure per hectare area. LD on organic dairy farms is equal to that on conventional farms (Swedish Board of Agriculture 2005; FADN 2008), as the subsidies for organic farming have resulted in some very large dairy or beef units by Swedish

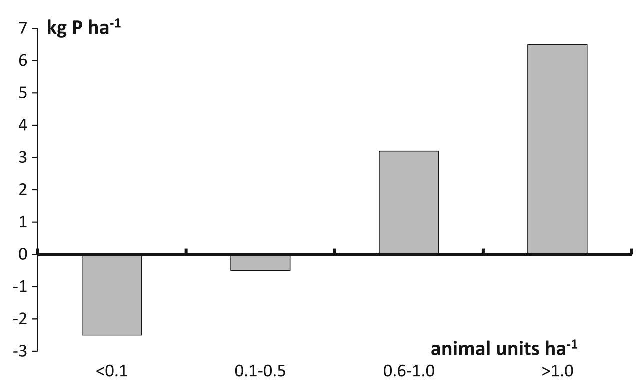

Fig. 2 Phosphorus balance on farms with different animal density ranges (based on data from Statistics Sweden 2011c)

standards (Swedish Board of Agriculture 2010f; Vadsbro Mjölk 2011).

However, Sweden was early in regulating permitted LD on farms to manure phosphorus content and not only nitrogen content (LSFS 1988). In 2007, the average LD was 0.78 ha^{-1} in the 27 EU countries. Sweden and Finland have lower values, 0.57 and 0.5 LD ha^{-1}, respectively, and Norway and Denmark have higher values, 1.22 and 1.72 LD ha^{-1}, respectively (Eurostat 2011a). Although Sweden has low average LD, the total quantity of manure produced in 2009 contained ~25 000 tons phosphorus (Statistics Sweden 2011c). This greatly exceeds imported mineral phosphorus and almost equals total phosphorus inputs to Swedish farmland (~27 500 tons; Table 1). To balance phosphorus at field level and not only national level, the phosphorus in manure needs to be used more optimally, i.e. less on farms with high LD and more on farms with few or no animals.

Uncertainty in Data

Data measured in terms of amount with regard to phosphorus are quite reliable, e.g. data on fertilizers, feed minerals, feed from ethanol production and sewage sludge. The most uncertain values are imports and exports of food and feed, where water content and phosphorus content must be estimated for every product. The composition of very dry products is easier to estimate and 90 % of feed imports consisted of very dry products such as mineral, extracted or toasted rapeseed and soybean. Data on food industry waste etc. were confirmed by experts from the industry. Uncertainty factors for the data were estimated as described in Hedbrant and Sörme (2001) and are presented in Table 1. The resulting variation in net annual input is between 11 000 and 15 500 tons P corresponding to 3.6–5.0 kg P per hectare.

CONCLUSIONS

Swedish agriculture has a positive phosphorus balance, i.e. phosphorus is accumulating in soils, mainly on farms with more than one animal unit per hectare.

If imports of mineral fertilizer ceased, the phosphorus balance for Sweden as a whole would still be positive due to high phosphorus imports in food and feed.

Optimal use of manure phosphorus could replace much of the phosphorus imported as mineral fertilizer.

Large-scale animal production has high-average animal density and surplus manure phosphorus on land. To meet phosphorus requirements on farms with few or no animals, a national phosphorus surplus is needed.

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