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ORIGINAL ARTICLE

A substance flow analysis of phosphorus in the food production, processing and consumption system of the Netherlands

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Abstract Phosphorus (P) is an essential nutrient in agriculture. In recent years 15–18 Mt of P was used as mineral fertilizer in the global food production chain. The major source of this fertilizer is phosphate rock which is unfortunately a finite resource. In the long term this necessitates efficient use of fertilizer and optimized recycling of P rich waste streams (including manure). In order to determine the potential for sustainable use of P we performed a 3-year substance flow analysis (SFA) for the Netherlands, a country characterized by its intensive agriculture and a high livestock density. Such conditions occur in various regions of the world and can easily result either in environmental problems or an unsustainable use of P. Annual quantification of P flows were performed in 2005, 2008 and 2011. These were not restricted to agriculture. Industrial, household/retail and the environmental P-flows were also included. Due to relatively high quantities of feed imports, the national P-surplus amounted to almost 60 Mkg P in 2005, decreasing to 42 Mkg in the year 2011. A large proportion of this reduction was considered to be due to reductions in P fertilizer use. The SFA provided an insight into the fate of the national P surplus and the potential for recycling. In 2011 the major part of the 42 Mkg of P surplus was observed in waste streams from society (23 Mkg, e.g. sewage sludge incineration ashes, household refuse). During this study these waste streams were not reused within the national food production system or elsewhere. The remainder of the surplus accumulated in agricultural soils (around 12 Mkg) or were emitted through surface water (almost 7 Mkg).

Keywords Phosphorus · Recycling · Substance flow analysis · Surplus · Waste · Soil accumulation

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Introduction

Phosphorus (P) is an essential nutrient in the food production chain and moreover a major limiting factor for plant growth almost worldwide. Since the introduction of P fertilizer increasing amounts have been applied to enhance plant production, in recent years more than 18 Mt P/a is mined (IFADATA 2012). P fertilizer is delved from P-rich deposits which are known to be finite. The size of the remaining deposits remains under discussion (Kauwenbergh 2010; Edixhoven et al. 2014). However, there is no doubt that when comparing the balance between depletion and formation rate, these deposits should be used as efficiently as possible and recycling should be optimized. Unlike another finite resource, i.e. fossil energy, there are no alternatives for the use of P in food and feed production.

However, the actual use of P resources seems far from sustainable: (1) unrecoverable environmental losses via erosion, leaching and runoff are substantial (Pimentel 2006) (2) the global reuse of animal manure for plant production is inadequate, often considered as a waste product, but also used for energy production (for cooking but also for large scale energy production) (3) accumulation of P occurs at locations with already a surplus of phosphorus, usually at locations with concentration of livestock (Schröder et al. 2011; Cordell 2010), whereas large areas in the world are more or less deprived of P (e.g. in Africa, South America) (4) food and feed losses occur throughout the production chain including the consumption stage (Cordell 2010), (5) a limited reuse of P rich waste streams occurs in developed countries (e.g. sewage sludge) and less developed countries, e.g. human waste (Liu et al. 2008).

On the other hand it has been estimated that the demand for mineral P fertilizer will increase in the coming decades as the global population is expected to increase by almost 50 % and globally more people include meat in their diet (Smit et al. 2009). Additionally, possible increases in the production of bioenergy crops on so-called marginal land have the potential to increase demand for amounts of P fertilizer in order to attain reasonable yields (Römer 2009).

All this necessitates that steps are taken to change the current 'once-through' usage of P in the food production chain (e.g. Cordell et al. 2011; Schröder et al. 2011) towards a more sustainable utilization implying that losses are minimized, fertilizer is used efficiently, animal manure and other secondary P-rich waste products are recycled and soil accumulation is avoided.

Sustainable use cannot be restricted to agriculture alone, but should address various societal issues such as changes to the menu of the global population, urbanization, the planning of sites for intensification of livestock, the organization of waste management and probably a necessity for innovative sanitation systems.

In this article we focus attention on the P flows in the Netherlands, a country with a very specialized and intensive agriculture but also with a large P surplus. These characteristics and associated problems can however also be found on a more regional scale throughout Europe.

What are the options for sustainable P reuse in a situation that the inflow of P through feed is resulting in a manure surplus considering the available arable area and when at the same time reuse is restricted by legislation? Under such a situation the need to recycle waste streams produced by society is minimal and economic incentives are simply not existing.

In order to shed light on this topic an initial quantification of existing P flows was performed to determine the national P flows. A thorough analysis of the national P flows within and outside agriculture is necessary to enable the investigation of topics relevant to Dutch conditions, including the effect of (1) reducing the livestock population (2) regulatory options with regard to P fertilization (3) manure processing followed by export (4) reducing or even abandoning P fertilizer, (5) recycling P-rich waste streams from society etc.

Various publications analyzing national P flows have been restricted to the agricultural sector (a.o. Senthilkumar et al. 2012). However, when considering the importance of recycling it becomes relevant to include also the food and feed processing and consumption sector. Therefore, this article on the national P flows includes agriculture but also industry (food, non-food and feed industry) and the retail/household sector.

The study presented here was performed to determine the national P budget, identifying and quantifying areas of inefficient P use and losses, and additionally to analyze the amount of P which can potentially be recycled in the Netherlands.

As a result this analysis determined in more detail the national P surplus. Next to accumulation in soil, the surplus P can end up in the environment but can also be withdrawn from the nutrient cycle. It is important to quantify these different end points. Soil accumulation and emissions to the environment are of special concern to the Dutch government. From 2006 onwards Dutch legislation has become more rigorous concerning P inputs in agriculture (P from mineral fertilizer is now included in regulations, P from mineral fertilizer and manure are considered equal, maximum allowed P fertilization levels are decreased). Therefore, substance flow analyses (SFA) for P were performed in 2005, 2008 and 2011. These 3 years allowed an evaluation of the effect of policy change on soil accumulation and fertilizer use along with other aspects of the national P budget.

Methodology and results

A substance flow analysis (SFA) for P provides a systematic assessment of flows and stocks within a defined system in space and time. We followed the method as described in the Practical Handbook of Material Flow Analysis (Brunner and Rechberger 2004). This approach guarantees a systematic assessment of the flows and stocks of phosphorus by strict application of the 'conservation of mass' principle. The software used was the STAN v.2 program (Cencic and Rechberger 2008) which visualizes flows and provides an assessment of all inputs, stocks and outputs. In the SFA, following Cencic and Rechberger (2008), *flows* and *processes* are distinguished. A process is defined as an entity where transformation, transport or storage of P may occur. Processes identified in this paper are for example *Arable Land*, *Manure* and *Food industry*. Accumulation may occur within a process (e.g. soil accumulation of P in *Arable Land*), but in other processes accumulation cannot occur; for example we assume that in the process *Manure* P cannot accumulate in time ($\sim$1 year), excluding minor changes during storage. The annual production of manure must have a destination: it is either exported, applied to agricultural soil or is incinerated. As mentioned previously, the underlying principle of an SFA is the conservation of mass, P is present in many materials (milk, fertilizer) and the element P moves from one material to another (e.g. from fertilizer to milk) but it cannot disappear. Flows between processes are calculated in million kg of P (Mkg P). A description of all flows in the analysis is given in Supplementary Table S1. Generally, main flow data [including import and export of (agricultural) products] were derived from the national bureau for statistics (Central Bureau for Statistics in the Netherlands (CBS) 2012a). More specific details on methodology (including data sources) can be found in two reports freely available via the internet (Smit et al. 2010a; Buck et al. 2012).

In Supplementary Table S1 a short description of the underlying assumptions and calculations is presented for each flow including references (Beukeboom (1996), CBS (2008), CVB (2007), Geraats et al. (2007), PDV (2007), Rijkswaterstaat Waterdienst (2012), Werkgroep Afvalregistratie (2012)). In addition, an estimation of the variation and the resulting value after reconciliation (balancing the data taking into account the uncertainties) are presented. The data reconciliation procedure is provided in the STAN program, more detail on this procedure can be found in Cencic and Rechberger (2008) and Brunner and Rechberger (2004). Only in a few cases the final values were substantially different from the input values.

System boundaries

This paper focusses on the P flows in national food production and consumption chains, including the major P flows in urban and industrial waste and import and export. Imported and exported products, and national production include: meat (including carcasses), fish, eggs, wool, milk and other dairy products, bones, arable and horticultural products, and animal manure. However, not all physical flows were included in the flow diagrams: the flow of transit products is transported through the Netherlands (e.g. through the seaport of Rotterdam) to other countries in Europe. These transit products were excluded from this analysis, only those products registered as imported or exported products by CBS (2012a, b) and the commodities board for animal feedstuffs (www.pdv.nl) were included. Also the amounts of rock phosphate imported by Thermphos (a company that in the study period processed rock phosphate for the production of elemental P and phosphoric acid) were not included in the flow assessment since the same amount of P was later exported.

Errors and uncertainty

Uncertainty surrounding the SFA results are presented in Supplementary Table S1. The STAN program calculates final uncertainties based on the initial uncertainty. Initial uncertainties depend on the source of the data.

An extended uncertainty analysis was executed in 2012 (Statistics Netherlands (CBS) 2012b) concerning the calculation of animal manure in National Statistics (Bruggen 2007). The estimates, calculations and results from this study were used in our uncertainty assessment. Uncertainties derived from this study are indicated ("st") in Supplementary Table S1. Any flows not included in the afore mentioned study, were estimated based on expert judgement, indicated with ("est"). In some cases (time series) the uncertainty was calculated as the standard error of the mean (indicated with "sem"). If errors had to be combined, the error propagation calculator was used (http://laffers.net/blog/2010/11/15/error-propagation-calculator/).

The P flow model for the Netherlands

Figure 1 summarizes the import and export P flows in the Netherlands and displays also the flows between the six major processes: *Industry*, *Agriculture*, *Household/Retail*, *Waste*, *Surface water* and *Lost P* (e.g. P in incineration ashes that is not recycled). Processes have a rectangular shape whereas flows are indicated with an arrow. Results from the STAN calculations and final uncertainties of all flows are shown in the oval shapes accompanying the arrows. Where applicable, accumulation of P is indicated *within* the rectangle (e.g. in *Agriculture* the total annual (soil) accumulation totalled 11.8 Mkg of P/a). Flows indicated with an *E* or *I* refer to exported or imported products (crossing the Dutch borders).

The processes *Agriculture, Industry* and *Waste* can be considered as subsystems containing further details on the various P flows within each process. In the subsystem *Agriculture* (Fig. 2) the processes include *Arable land*, *Grazing and Maize land*, *Grazing animals* and *Intensive Livestock*. *Grazing and Maize land* is defined as land grazed by animals (grassland) plus the area used for silage maize production. This aggregation was formed because silage maize production is usually an activity of dairy farms. *Arable land* is defined as land used for growing arable and horticultural crops

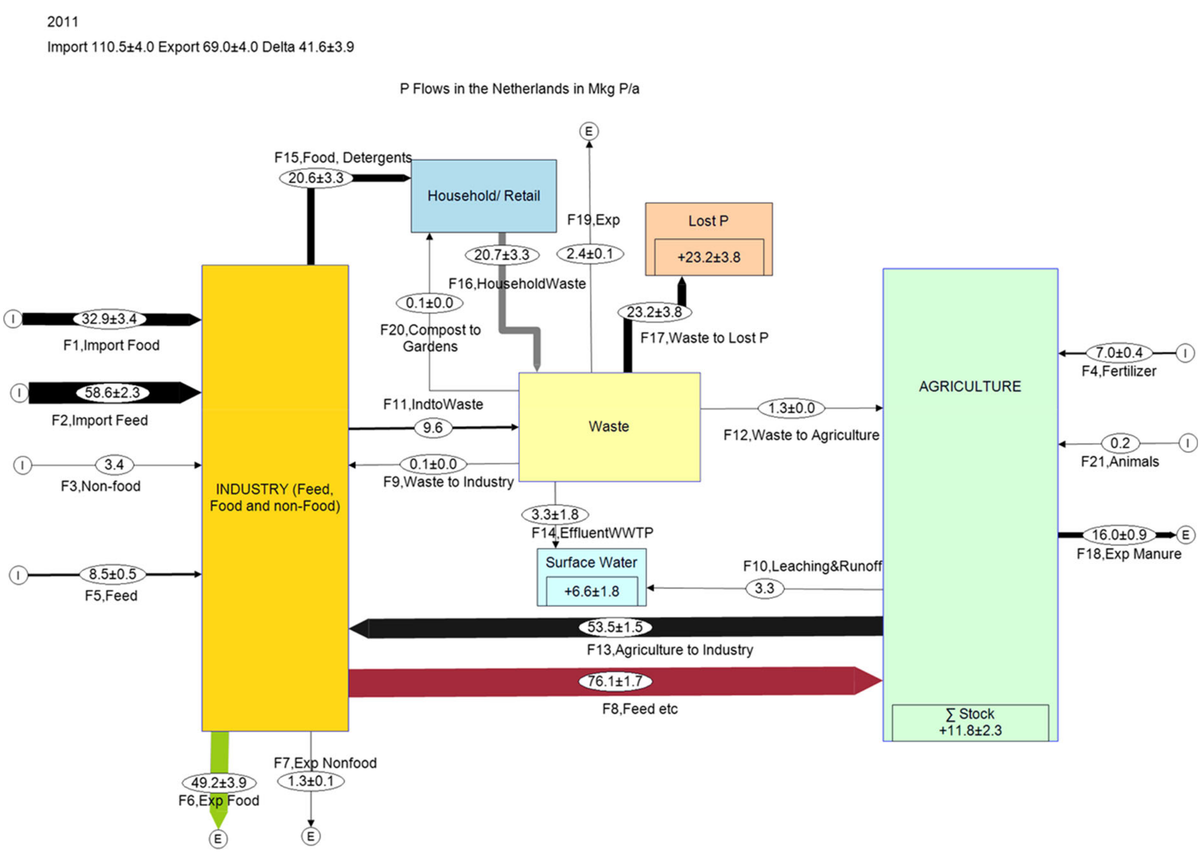

Fig. 1 P flows in the Industry, Agriculture, Household/Retail, Waste and Surface water systems in 2011 (Mkg P/a)

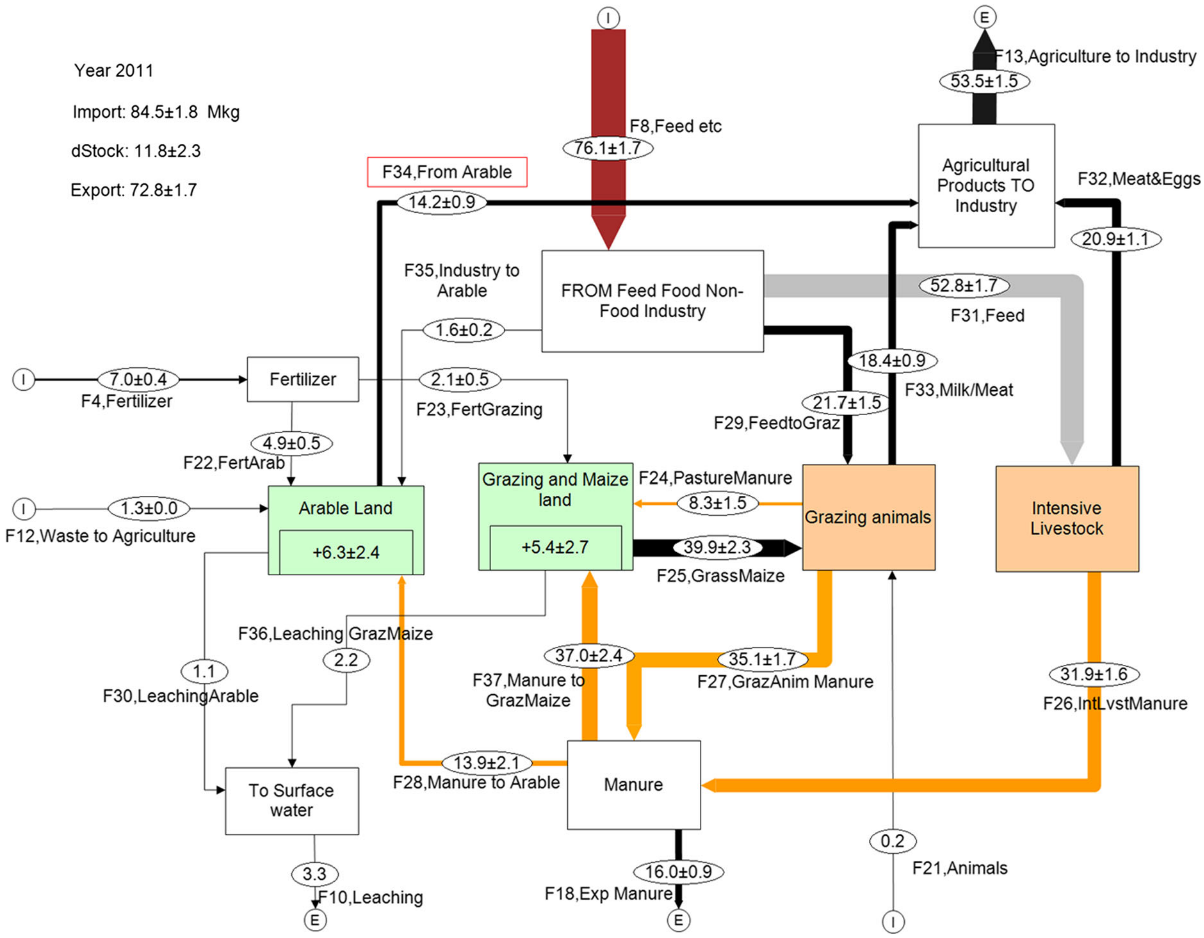

Fig. 2 P flows in the agricultural subsystem in 2011 (Mkg P/a)

excluding silage maize but including alfalfa (lucerne) and grain maize. Cropping areas were derived from the CBS statistics for the 3 years under investigation (Statline database (Statline 2012)).[1] In this flow diagram (and those subsequent) the flows with an *E* or an *I* can refer to either national import/export (crossing Dutch borders, e.g. flows F4, F21 and F18) or to flows having an internal national origin/destination [e.g. flow F8 (Feed etc.) is the flow from *Industry* to *Agriculture*].

For the subsystem *Industry* a distinction was made between *Feed*, *Food* and *non-Food industry* (Fig. 3).

Figure 4 shows the flows identified within the subsystem *Waste*, important processes include the industrial and communal waste water treatment plants (WWTP). Data on the amount of sewage sludge and its destination were collected from Statline (2012). The P content was only assessed in the sludge produced in communal WWTP. For the sludge from the industrial WWTP we assumed a P content of the dry sludge of 2.24 % (see Supplementary Table S1 for a justification of this percentage). By assuming a P removal efficiency of 82 % (see Supplementary Table S1) we calculated the input to WWTP and, consequently, the P in the effluent that ends up in the surface water. In Supplementary Table S1 more details, including references, can be found which refer to the relevant flows in this domain. Figures 1, 2, 3 and 4 display the flow values for 2011, changes in time were analysed by performing the same analysis for 2005 and 2008, year 2005 was considered as the reference year. The changes in the P balance for the various processes during this period are shown in Table 1 and in Supplementary Table 2 to 9.

[1] This references include the data for preceding years.

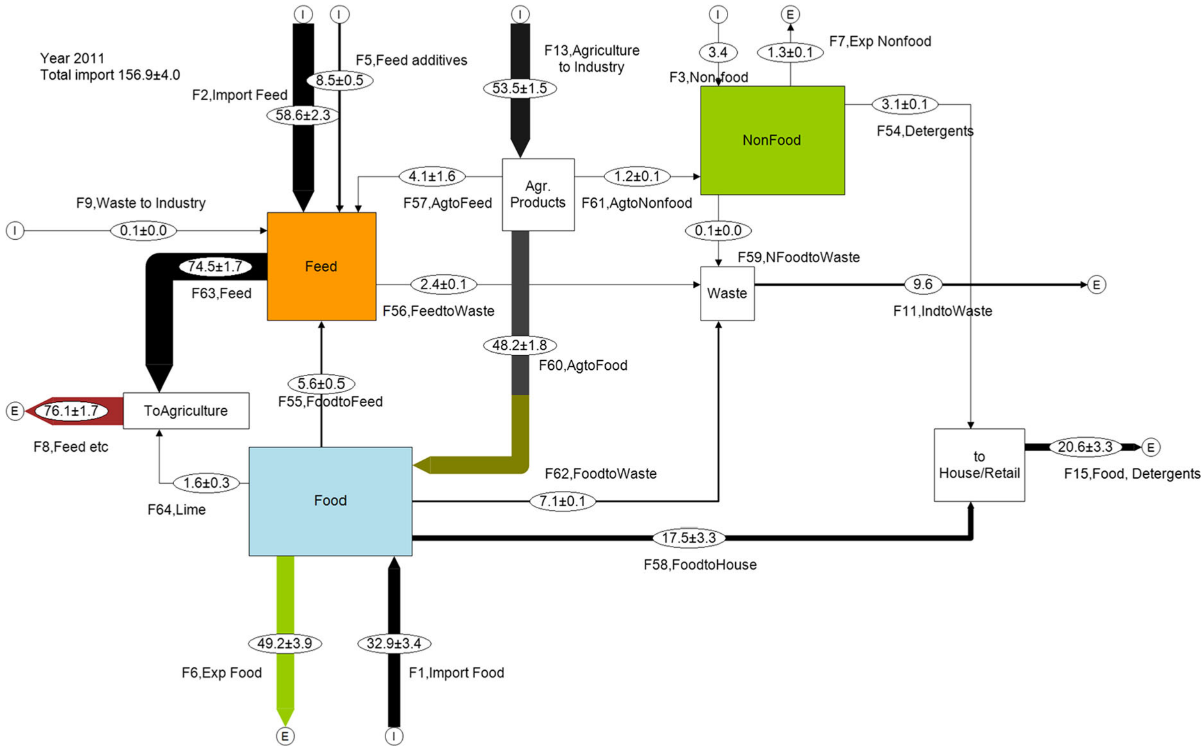

Fig. 3 P flows in the industry subsystem in 2011 (Mkg P/a)

Analysis

Before considering the overall picture of the national P flows in Fig. 1, the subsystems *Agriculture*, *Industry*, *Household/Retail, Waste*, *Surface Water and Lost P* will be discussed.

Agriculture

The P flows within the subsystem *Agriculture* in 2011 are presented in Fig. 2, which also in the left upper corner presents the total import, export and accumulation (dSTock) of P for this subsystem. The main inflow of P into the system consists of imported or nationally produced feed processed in the feed sector (F8) and fertilizer (F4).

The main outflow of P from the agricultural system (F13, the same flow is also visible in Fig. 1) consists of products passing on to the industry and include, next to animal produce, also nationally produced feed (excluding produced grass and silage maize) and food crops (F34). Soil accumulation of P occurs in both *Arable land* (6.3 Mkg/a) and in *Grazing and Maize land* (5.4 Mkg/a).

For the processes *Arable Land* and *Grazing and Maize land* Supplementary Table S2 and Table S3 present the data for the years 2005, 2008 and 2011. The most significant change in these years is the reduction in fertilizer use, in *Arable land* decreasing from 9.3 in 2005 to 4.9 Mkg P in 2011, a larger reduction was observed in *Grazing and Maize land* (from 11.7 to 2.1 Mkg P). Consequently, the total national use of P fertilizer in the period 2005–2011 fell from 21.0 to 7.0 Mkg P/a. On *Grazing and Maize land* also the use of manure decreased while on arable land there was a slight increase. In 2011 this increase provided only a slight compensation for decrease in mineral fertilizer use. Other inputs and outputs differed only slightly between the years.

Total accumulation in *Arable land* decreased from 8.3 of P in 2005 and 2008 to 6.3 Mkg P in 2011 corresponding to 12.5 and 9.6 kg P/ha (taking into account the acreage of 0.6 Mha arable land in the Netherlands). The ‘efficiency’ of the *Arable* sector, defined as the amount of P in arable products (Food,

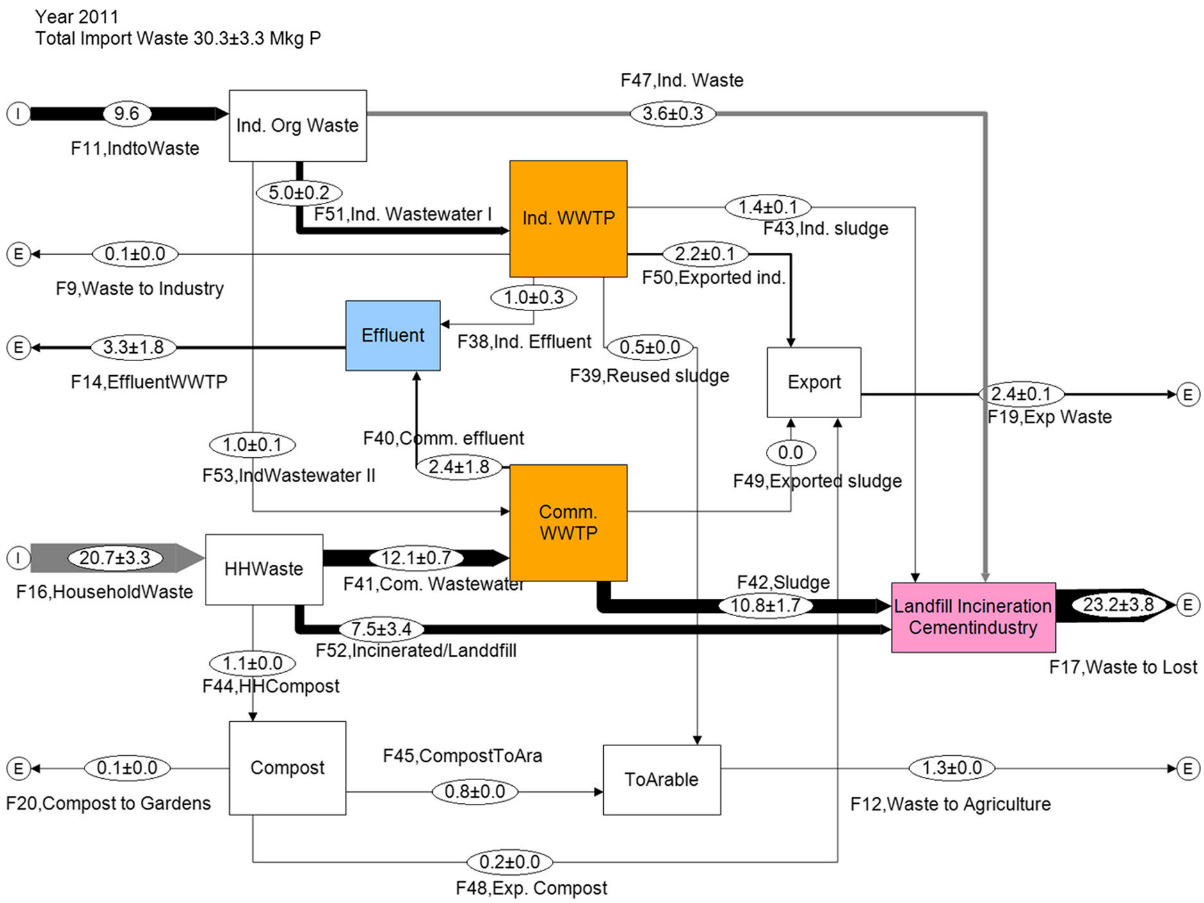

Fig. 4 P flows in the waste subsystem in 2011 (Mkg P/a)

Table 1 National P balance of the Netherlands in 2005, 2008 and 2011 (Mkg P/a)

	Subsystem	Products	2005	2008	2011
National balance					
Import	Agriculture	Fertilizer	21.0	12.0	7.0
		Living animals	0.2	0.2	0.2
	Industry	Feed	50.4	60.1	58.6
		Non-food	1.4	3.3	3.4
		Food	28.0	31.1	32.9
		Feed additives	7.2	8.1	8.5
	Total import*		*108.2*	*114.8*	*110.5*
Export	Agriculture	Manure	7.0	12.8	16.0
	Industry	Food	37.5	47.6	49.2
		Non-food	1.3	1.2	1.3
	Waste	Waste	2.7	2.0	2.4
	Total export*		*48.5*	*63.6*	*69.0*
	Balance*		*59.7*	*51.2*	*41.6*

* Italics indicate totals

Feed and non-Food) divided by the total input of P, increased slightly from 61 in 2005 to 65 % in 2011.

Soil P accumulation on *Grazing and Maize land* decreased considerably from 23.0 to 5.4 Mkg P/a (corresponding with 19 and 4 kg P/ha, respectively). The 'efficiency' (considering crops, grass and maize as output and manure and fertilizer as input) increased substantially from 61 in 2005 to 84 % in 2011 (Supplementary Table S3).

The inflows and outflows of the *Grazing Animals* process is summarized in Supplementary Table S4. Total inflow and outflow amounts to approximately 60 Mkg of P/a. No considerable differences were observed in input and output flows between the 3 years. From the total inflow 27–29 % (16–18 Mkg P/a) was converted to the outflow from animal products (milk and meat, as whole animals), the remaining P was in manure (43–45 Mkg P).

For the process *Intensive Livestock* (Pigs and Poultry) the inflow with concentrates increased from 44.4 to 52.9 Mkg P/a from 2005 to 2011 (Supplementary Table S5), corresponding with an increased outflow of animal products (eggs and meat) and manure. About 35–39 % of the total input was recovered in useful animal products (meat, whole animals and eggs).

Industry

Figure 3 presents the subsystem *Industry* and visualizes the P flows between the processes *Food*, *Feed* and *non-Food industry* in 2011. Phosphorus flows in the feed industry are dominated by the import of feed compounds, 58.6 Mkg P (flow F2) and to a lesser extent feed additives (8.5 Mkg P,flow F5). Domestically produced feed (crop products, flow F57) and by-products from the food industry (flow F55) contribute 9.7 Mkg to feed industry P levels.

The main influx to the food industry is provided by domestically produced agricultural products (48.2 Mkg P, Flow F60) and imported food products (32.9 Mkg P, flow F1). Exported food products were estimated to contribute 49.2 Mkg P (F6). This export flow includes export of bone (meal and chips) (used outside the Netherlands for fertilizer and porcelain production). Additionally, the food industry produced also 7.1 Mkg P in waste streams (F62) which is processed by the *Waste Industry*. However, only 17.5 Mkg P enters the *Houshold/Retail* sector in food products (F58).

Phosphorus flows in the non-food industry are relatively small. A major outflow of P is detergents in the Household/retail sector (3.1 Mkg P in 2011, F54).

In between the analysis years large industrial P flow variations were observed in imported feed and exported food (Supplementary Table S6). This was a consequence of a large increase in imported feed wheat from 2005 to 2008/2011. The number of animals also increased during our observation years but not to such an extent as to justify such increases of feed intake. Feed intake is quite accurately determined by the CBS through direct data exchange with the feed industry. However, it is possible that some wheat was used for human consumption but such a strong increase in national human consumption is not thought plausible. Therefore it was assumed that the extra imported wheat was exported again (or domestically produced wheat instead) but not registered. In the EU it is not obligatory to register exports to other EU-member states. Therefore we increased the export of arable products as food (including wheat). Possibly this is a consequence of the uncertainty in the statistics as the choice between transported products or actual imports into the Netherlands is difficult to access (see also section Methodology). This uncertainty is also expressed in import and exports in Supplementary Table S1.

Household and retail

Supplementary Table S7 presents an overview of the inflows and outflows of the *Household/Retail* process. Food entering this section was calculated as the difference between imported and domestically produced food products minus exported food products (including pet food). In all 3 years total P input amounted to approximately 20 Mkg P/a. The increase in non-food between 2005 and 2008/11 is partly due to the fact that values for 2011 were based on more accurate data that have only recently been published (see Supplementary Table S1, flow F54).

On average 30–40 % of the P in food products entering *Household/Retail* were of vegetable origin and approximately 60–70 % of animal origin. In 2011 the latter amounted to 10.7 Mkg P and included dairy products (4.2 Mkg), meat (3.2 Mkg), eggs (0.5 Mkg), fish (1.9 Mkg) and pet food (1.0 Mkg P). Food entering the *Household/Retail* is not completely consumed, it also contains waste discarded prior to consumption (e.g. leaves and peelings from vegetables, cutting losses from meat, shells from eggs). Additionally, it also includes perishable food which is discarded due to exceeding the recommended expiry date. Assuming that there is no accumulation, therefore, the whole P inflow exits via household waste. Supplementary Table S7 shows that 6–9 Mkg P/a from the Household/Retail system is eventually incinerated (landfill is currently not a major sink in the Netherlands for refuse). About 30–40 % of the *Household/Retail* input is refuse which corresponds with Swiss data reported by Binder et al. (2009).

Waste management

The inflow of waste from the industry amounted to 9.6 Mkg P in 2011 (Fig. 4, F11). The major part originates from the food industry and includes high risk slaughter waste processed by a specialized company (Rendac) and eventually incinerated (F47). About 5 Mkg P in waste water is processed by Industrial WWTPs, P intercepted in the industrial sewage sludge was either reused in agriculture (F39), exported (F50) or incinerated (F43). In 2011 1.0 Mkg P in industrial waste water was processed by communal WWTPs (F53).

The amount of P in sludge from communal WWTPs amounted to 10.8 Mkg/a (F42). Based on efficiency assumptions for these WWTPs (Supplementary Table S1) we are able to estimate the P input with household sewage water at 12.1 Mkg P (F41). Taking into account that 1.1 Mkg P from household/retail is processed through compost (F44) we estimate that 7.5 Mkg P of the household waste ends up in incineration plants or in landfill (F52). As explained in Supplementary Table S1 this constitutes a rest flow, which could be calculated assuming that no accumulation occurs in the household sector.

Supplementary Table S8 summarizes the input and output of the Dutch Waste sector in 2005–2011. Total input in the 3 years was approximately 30 Mkg P, two-thirds coming from *Household & retail* (sewer, household refuse etc.) and one third from industrial waste. The output of the waste sector shows that only minor amounts of waste are reused in agriculture or exported and that the major part is either lost to the environment or sequestered, respectively 24.9, 28.4 and 26.2 Mkg of P in 2005, 2008 and 2011.

Environment and sequestered

Supplementary Table S9 summarizes the P flows which can be considered as withdrawn from the food production chain (emitted to the environment or deposited in incinerations ashes or cement plants). Annually, more than 6 Mkg P is deposited in surface water, half of which originates from industrial effluent and communal wastewater treatment plants. The other half can be attributed to leaching and runoff from agricultural land. Eventually 21–25 Mkg P is sequestered in either incineration ashes or cement.

The national balance

Table 1 and Fig. 1 present the phosphorus flows aggregated at national level. In the period 2005–2011 fertilizer imports decreased from 21.0 to 7.0 Mkg P/a, whereas the import of feed products increased from 50.4 to 58.6 Mkg P/a. The import of food as well as feed additives increased slightly. Total import of P increased between 2005 and 2008 and decreased in 2011 to a comparable level as observed in 2005. Total P export increased by more than 20 Mkg P/a (from 48.5 in 2005 to 69.0 Mkg P in 2011), mainly caused by increased exports of manure and food products. Consequently the national P surplus decreased from 59.7 in 2005 to 41.6 Mkg P in 2011. Figure 1 displays the fate of this surplus (the spots of accumulation) in 2011: soil accumulation in *Agriculture* (11.8 Mkg P), losses to *Surface Water* (F14, 6.6 Mkg P) and sequestering in *Lost P* (F17, 23.2 Mkg P).

Discussion

Characterization of the P budget in the Netherlands

The national P budget in the Netherlands is characterized by relatively large net imports of P with feed, minimal recycling of P in waste flows and a large national surplus (41.6 Mkg P in 2011). Phosphorus flows in the sector waste management are either not recycled or perpetually withdrawn from the food production cycle. The flow of P destined for construction material, incineration ashes from sewage sludge or household refuse is substantial, 20–25 Mkg P/a. However, since 2011 the P-rich incineration ashes from sewage sludge have been increasingly utilized as input for the fertilizer industry (Marcel Lefferts, pers. comm, Slibverwerking Noord-Brabant; SNB).

In addition, about 20 % of the total input flow to wastewater treatment plants is not intercepted (about 3 Mkg P/a), emits to surface water and will eventually end up in the ocean sediments. The same applies to the P lost through leaching and runoff from agricultural land (about 3 Mkg P/a). Therefore, the annual deposit of P in the Dutch surface water is estimated at 6–7 Mkg P (Supplementary Table S8) and will eventually become available again in the distant future [millions of years, (Smil 2000)].

The remainder of the national surplus yearly accumulates annually in agricultural soils. Supplementary Table S2 and Table S3 indicate a significant reduction occurred from 2005 to 2011 (from 31.3 to 11.7 Mkg of P/a in total for all agricultural soils). However, despite this decrease almost 30 % of the national surplus still accumulated in agricultural soils in 2011.

The effect of legislation on improved P management in agriculture

In 2006 new legislation was introduced in the Netherlands for allowance of maximum N and P fertilization levels in crops. The main goal being to limit N and P emissions in order to meet European quality standards for ground- and surface water (e.g. http://ec.europa.eu/environment/water/index_en.htm).

Before 2006 the standardized nutrient balance sheet system (MINAS) was used but this system did not account for mineral fertilizer-P.

In 2006, legislation restricted the total P allowance to grassland and arable land to 48 and 41 kg P/ha, respectively. In 2008 these levels were further reduced to 44 and 37 kg P/ha. Further, in 2010 P fertilization rates restricted by relating P rates to soil P status. On soils with a high P status lower P application levels were allowed than on soils with a low P status (Ministerie van Landbouw Natuur en Voedselkwaliteit [Ministry of Agriculture] 2009). On average this resulted in a maximum P fertilization allowance of 42 kg P/ha for grassland and 33 kg P/ha for arable land.

Our analysis showed that stricter legislation resulted in a substantial decrease in the national soil surplus from 31 Mkg P in 2005 to 19.3 and 11.7 Mkg P/a in 2008 and 2011, respectively.

The reduction in 2008 appears to be entirely attributable to the subsystem *Grazing and Maize land* as the accumulation rate in Dutch arable soils was essentially the same in 2005 and 2008. In *Grazing and Maize land* the accumulation fell from 19 kg P/ha in 2005 to 9 kg P/ha in 2008 and to 4 kg P/ha in 2011. Accumulation on arable land decreased with not more than 30 % to 9.6 kg P/ha in 2011 in comparison to 2005 and 2008. Supplementary Table S3 indicates a reduction for manure and especially for mineral P fertilizer in *Grazing and Maize land*. These type of farms will initially use locally produced manure as the use of mineral fertilizer will increase the need to apply the manure elsewhere resulting in higher costs. This explains why a reduction of mineral P fertilizer is much higher than for *Arable Farms* that have lower or no manure production.

As shown in France, a large spatial variation occurs between areas with and without intensive livestock. In France the national average balance decreased from 17.5 in 1990 to 4.4 kg P/ha in 2006. However, in 2006 it ranged from 17 kg P/ha in Brittany, a region with a high livestock density, to 0 kg P/ha for the Central region with a low livestock density (Senthilkumar et al. 2012).

For the United Kingdom (Cooper and Carliell-Marquet 2013) reported that P accumulation for arable land, grassland and total agricultural land was 2.5, 4.2 and 3.5 kg P/ha/a, respectively. Ott and Rechberger (2012) mention for the EU-15 an accumulation rate on agricultural land of 2.9 kg P/capita/year. This corresponds to 8.6 kg P/ha per year assuming that the agricultural land area in the EU-15 is 135 Mha and the population was 400 M inhabitants. For the Netherlands soil accumulation in agriculture on a per capita basis would be about 0.75 kg P/capita/year, substantially lower than number mentioned by Ott and Rechberger (2012). This is probably because of the high population density of the Netherlands.

P efficiency of the agricultural sector

According to our definition of P use efficiency in agricultural (sub)systems (the P input fraction converted into useful products i.e. crops, dairy products and animal tissues), P emission, manure excretion and soil accumulation all have a negative influence. However, it must be kept in mind that we compare complete systems, a positive trend in efficiency does not necessarily mean that animals or plants become more efficient in time, changes in farm management have potentially a greater effect.

Supplementary Tables 2 to 5, present the efficiencies for *Arable land*, *Grazing and Maize land*, *Grazing animals* and *Intensive livestock* subsystems, respectively. Efficiency increased in all subsystems from 2005 to 2011. Efficiency of land based systems was much higher than in animal husbandry.

The efficiency of the *Grazing and Maize land* subsystem increased from 61 in 2005 to 84 % in 2011 (Supplementary Table S3). This increase was caused by the reduction in mineral fertilizer-P use. The efficiency of the arable sector rose from 61 in 2005 to 66 % in 2011.

No trend in the efficiency in the *Grazing animals* and *Intensive livestock* subsystem was observed (around 28 and 37 % resp. for the 3 year period). According to Cooper and Carliell-Marquet (2013) the P efficiency of UK crop production was 81 %, whereas the efficiency of animal products was only 16.5 %. These differences between the two countries can be attributed to the higher P accumulation in Dutch soils and a more efficient conversion from feed to animal products in the Netherlands compared to the UK.

Options for a more sustainable use of P

Livestock in the Netherlands produce more manure than can be used sustainably on the agricultural land. Despite the decrease in the maximum P application allowance on agricultural land it has been estimated that in 2015 P accumulation in Dutch soils will remain at about 10 Mkg of P/a (Buck et al. 2012). Assuming that, in the short term, P crop offtake will not change substantially, decreasing the soil surplus is only possible by reducing the maximum levels of P fertilization allowance, which will further increase the manure P surplus. Therefore, current mineral policy focuses on technologies for manure processing, enabling the export of P-rich processed manure products in an attempt to diminish the P surplus. However, in order to limit or reduce transport costs these products must have a low volume.

Even in regions that do not have a manure surplus soil accumulation may occur when the national P fertilizer recommendation is adhered to. Accumulation is desired when the P fertility status of the soil requires improvement. In a review of P-fertilizer recommendation strategies, Römer (2009) concluded that 70–80 % of European agricultural land has an average or high level P-status. It was argued that in these regions yields can be maintained without P-fertilization and a P application would increase yields. In Germany, as in most other countries, a specific range of soil fertility level is recommended. Usually soil P-fertility is assessed by extraction with weak acids or water estimating the amount of plant available P. Römer (2009) concluded that a minimum application of 500 kg P/ha would be required to raise soil fertility from the lowest to the highest level. Such an amount is exported by crops in about 20 years.

It is questionable whether all crops require the highest soil fertility level for a sustainable yield. On less fertile soil a localized application of small amounts of P placed (e.g. banding) instead of a broadcast could produce the same yields (Smit et al. 2010b). Obviously, accumulation of P in soils needs to be reduced in order to avoid long term negative environmental effects (Reijneveld et al. 2010).

Recycling of urban waste P would contribute to a more sustainable use of P, the flow from the Dutch society now ends up in sewage sludge and solid waste. In Europe 50 % of sewage sludge is reused in agriculture, in the UK 71 % is recycled (Cooper and Carliell-Marquet 2013). In the Netherlands virtually no communal sewage sludge is recycled due to the heavy metal content and is therefore incinerated. Disregarding contaminants the Dutch agricultural sector would be reluctant to reuse the sludge due to concerns about the maximum P application allowance. At the WWTP's usually Fe or Al compounds are added during the purification process to precipitate P. However, the Al and Fe phosphates are less water soluble and thus reducing their availability for plant uptake. In a situation where P fertilization is restricted, as is the case in the Netherlands, application of sewage sludge with a low P availability is less favourable to on-farm use than mineral fertilizer or animal manure.

Application of incinerated sludge ash was also demonstrated to contain P with a low P availability for plants (Postma et al. 2011). Linderholm et al. (2012) assessed four P supply methods in Swedish agriculture in a life cycle analysis: (1) mineral fertilizer, (2) certified sewage sludge, (3) struvite originating from wastewater and (4) P recovered from sludge incineration. It was concluded, that application of sewage sludge on farmland was the most efficient option in terms of energy and emissions of greenhouse gasses, while adding the most cadmium to the soil.

In the Netherlands awareness is growing that technologies need to be developed for recovering P from incineration ash for fertilizer. Recently, many WWTPs have shown interest in the recovery of P through struvite. Struvite can be used directly as fertilizer (Johnston and Richards 2003) or can be used as input for the fertilizer industry. An additional advantage for WWTPs would be that a struvite plant would improve the dehydration of sewage sludge and consequently reduce cost. In 2011 in the Netherlands (See Supplementary Table 9), about 23 Mkg of P (more than 50 % of the national surplus) could potentially be reused if cost effective technologies had been available. However, a domestic recycling is not a formality considering the relatively small amount of mineral P fertilizer used in the country (7 Mkg in 2011). Export of recycled P becomes then a necessity, but in the case of struvite this is a feasible option.

Reducing the number of animals in the Netherlands does not appear to be a viable option, but a reduction of P in feed using feed with a lower P content and reductions in additive use are promising. Reduction of phosphorus in concentrate feed is possible without great extensive technical effort and without significant consequences for production. At present the feed industry is working on phosphorus reduction in concentrate feed for dairy cattle and intensive livestock. The Dutch agricultural farmers organization (LTO) and associated feed industry (NEVEDI) have agreed on a 10 % reduction in concentrate feed phosphorus content in 2015.

Awareness in the Netherlands led to the so-called Phosphate Chain Agreement in 2011 (see www.nutrientplatform.org). Under this agreement farmers organisations, industry and the waste sector have joined forces for improving P efficiency. The developed model may now be used to monitor this agreement and study its impact.

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