CHALMERS
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Assessing the Possibility of a Circular Economy for Phosphorus in Sweden

Master's thesis in Industrial Ecology

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019
Report No. E 2019:114

MASTER'S THESIS E 2019:114

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Chalmers digitaltryck

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Abstract

Phosphorus is essential for all biological life, and as such it is necessary for biomass production. Today, most of the phosphorus in agricultural fertilizers originates from mineral reserves, which are steadily declining both in terms of quantity and quality. Estimates for when the mineral phosphorus fertilizer production will reach its peak vary, with some estimates suggesting that it will peak as soon as 2030. Moreover, mineral phosphorus is not equally distributed around the globe, with a few nations controlling a majority of the mineral reserves. In addition to the scarcity problems, emissions of phosphorus can lead to excessive growth of algae and cyanobacteria, which causes anoxic bottom zones. This has been a severe problem in the Baltic sea, which stretches along the eastern coast of Sweden. The aim of this thesis was to evaluate if a circular economy for phosphorus is possible in Sweden. To aid with the evaluation, a Material Flow Analysis (MFA) was conducted for phosphorus in Sweden. The recirculation potential of different phosphorus-containing waste flows was then assessed based on the magnitude, concentration, chemical form or plant availability, contamination and geo-spatial availability of the flows. This thesis found that there is a large potential for improving phosphorus management, especially regarding the utilization of sewage sludge from municipal wastewater treatment and ashes from the forestry sector. There is also a large amount of phosphorus in mining waste, which in the future could potentially be used for fertilizer production. It is concluded that the amount of phosphorus in flows fit for recirculation is not sufficient to replace mineral phosphorus with current demand, unless the phosphorus in mining waste is used. Thus, to achieve a circular economy for phosphorus in Sweden, production sectors have to become more resource-efficient in their phosphorus usage. The agricultural sector is pointed out as an area with particularly high potential for improvement in this regard.

Keywords: Phosphorus, Nutrient flow analysis, Circular economy, Food security, Material flow analysis, MFA, Sweden

Acknowledgements

I would like to express my sincere gratitude to my supervisor, Dr. Robin Harder, and my examiner, Professor Magdalena Svanström, for their invaluable guidance in this project and for the opportunities they have provided me with. I would also like to thank Professor Christel Cederberg for taking the time to answer questions about agricultural practices and statistics. Lastly, I would like to thank the employees at Gryaab for the interesting discussions we had.

Contents

1. Introduction

Modern society is dependent on the production of biomass for such things as food, materials and energy. Biomass production in turn requires an input of plant nutrients, including phosphorus. But even though biomass production in the form of agriculture has been around for at least some ten thousand years (Ponting, 2007), the importance of phosphorus was not realized until relatively recently. Phosphorus is essential for all biological life. It is required in several important biological functions: it is present in compounds such as DNA, RNA and ATP, and it is a key component of cell membranes (Butusov & Jernelöv, 2013). An adult human contains around three quarters of a kilogram of phosphorus (Helmenstine, 2019). The first phosphorus fertilizer was produced from animal bones in the early 1800s (Russel & Williams, 1977), and since then, territories have been occupied and wars have been fought over this precious element (Reijnders, 2014).

Today, most of the phosphorus in agricultural fertilizers originates from phosphate rock deposits. Current reserves, in the form of concentrated deposits of high-quality ore, are steadily declining both in terms of quantity and quality (Cordell & White, 2014). New reserves are forming very slowly through sedimentation in the oceans and tectonic processes. Some scholars have suggested that 'peak phosphorus', i.e. a peak in mineral phosphorus fertilizer production stemming from dwindling rock phosphate reserves, will occur as soon as 2030 (Cordell et al., 2009). Others argue that a peak is unlikely to occur this century (Van Vuuren et al., 2010) or will not occur at all (Scholz & Wellmer, 2013). In addition, phosphate rock deposits are not equally distributed throughout the globe. Europe only has one mine, situated in Finland, which constitutes around one percent of the world's total production (Ahokas, 2015). According to estimates from 2010, two thirds of the world's production is controlled by Morocco, USA, and China (Reijnders, 2014). In terms of reserves, around 70% of the remaining mineral phosphorus is located in the Morocco-occupied Western Sahara (US Geological Survey, 2019).

As well as being scarce, phosphorus is also the most common limiting factor for algae growth in freshwater systems (Correll, 1999). As such, emissions of phosphorus can lead to excessive growth of algae and cyanobacteria, which causes anoxic bottom zones. This has been a severe problem in the Baltic sea, which stretches along the eastern coast of Sweden (Larsson et al., 1985). According to the authors of the Planetary Boundaries concept, the phosphorus and nitrogen cycles are currently the most severely mismanaged natural boundaries, alongside biodiversity (Steffen et al., 2015).

To secure future biomass production and end excessive eutrophication, it is essential to close the loops in today's linear usage of phosphorus. To achieve that, current phosphorus flow patterns first have to be understood. National phosphorus balances have been conducted for example for Austria, Switzerland, Norway and Sweden. These studies have varied in scope and level of detail as shown in Table 1. The previous studies of phosphorus flows in Sweden have been a tremendous asset and source of inspiration for this thesis.

Table 1. Examples of earlier national phosphorus balances. "National sectors" refer to different sectors within the nation's borders, e.g., production or waste treatment. Examples of such sectors can be seen in Figure 1.

Authors	Country	Scope	Resolution
Egle, Zoboli, Thaler, Rechberger & Zessner, 2014	Austria	Quantification of current national stocks and flows	Stocks and flows of national sectors, imports and exports
Jedelhauser, Mehr, & Binder, 2018; Mehr, Jedelhauser, & Binder, 2018	Switzerland	Quantification of current and historical national stocks and flows, socio-technical scenarios for a circular economy	Stocks and flows of national sectors, imports and exports

Hamilton et al., 2017, 2016; Hanserud, Brod, Øgaard, Müller, & Brattebø, 2016	Norway	Soil balances, quantification of current flows in food chain, plant availability of residual flows	Soil balances on regional level, flows in food chain on national level, imports and exports
Linderholm & Mattsson, 2013; Linderholm, Mattsson, & Tillman, 2012; Staaf, 2013	Sweden	Quantification of current flows	Flows to and from the production system for national sectors, flows within forestry, imports and exports

The aim of this thesis is to evaluate if a circular economy for phosphorus is possible in Sweden. This is done through answering the following questions:

- How large are the phosphorus flows of different Swedish sectors, and where does the phosphorus end up?
- How much phosphorus is recirculated through residual flows to production sectors in Sweden today? What amount of phosphorus is technically possible to recirculate?
- Are there any stocks or flows of phosphorus of particular importance regarding size, chemical form or plant availability?
- Are any stocks or flows contaminated? What treatment would be required to make these useful?
- Is there enough phosphorus in different flows to support Swedish needs, regarding agriculture as well as other industry, if the inputs of mineral phosphorus were to cease?
- Can any specific policies be implemented to help achieve a circular economy for phosphorus?

In order to form a basis on which the potential for a circular economy can be judged, this thesis attempts to first map out all of the major flows of phosphorus in Sweden. This includes flows within national sectors, some of which were not quantified in previous studies. An example of such a flow is the amount of phosphorus in harvested crops. To further strengthen the basis on which phosphorus recirculation can be discussed and policies can be formed, this thesis also aims to identify flows with potential for recirculation and characterize these according to their size, concentration, chemical form or plant availability, contamination and geo-spatial limitations.

It should be noted that this thesis is limited to phosphorus. However, there are several other important macro- and micronutrients. If phosphorus is the only nutrient that is considered when policies and strategies are formed, there is a significant risk for sub-optimization.

2. Method

The study consisted of two parts: (1) estimating phosphorus flows for Sweden, and (2) evaluating if a circular economy for phosphorus is possible. Both parts were largely based on existing literature and statistics on for example the import of mineral fertilizer, agricultural and industrial practices, and waste treatment.

2.1 Conceptual model

A conceptual model of the system can be seen in Figure 1. This model was created through reviewing existing literature, mainly in the form of earlier studies of national phosphorus flows, and served as the starting point for the data gathering and calculations. Note that another version of this figure, indicating the actual magnitude of the flows, can be found in section 3.9. It should be noted that the box named “Landfill or equivalent” includes uses in which phosphorus is lost from the industrial production system. For example, this includes constructing roads with wastewater sludge, and applying compost in private gardens. This was done partially to avoid cluttering of figures, and partially to accentuate that such uses are a waste from the perspective of industrial production. It could, however, also be argued that these uses are justified since they offer utility in other ways. It should also be noted that rock weathering and atmospheric deposition were not quantified in this study, since that was deemed to be beyond the scope of this thesis. Atmospheric deposition is discussed briefly in Appendix 2.

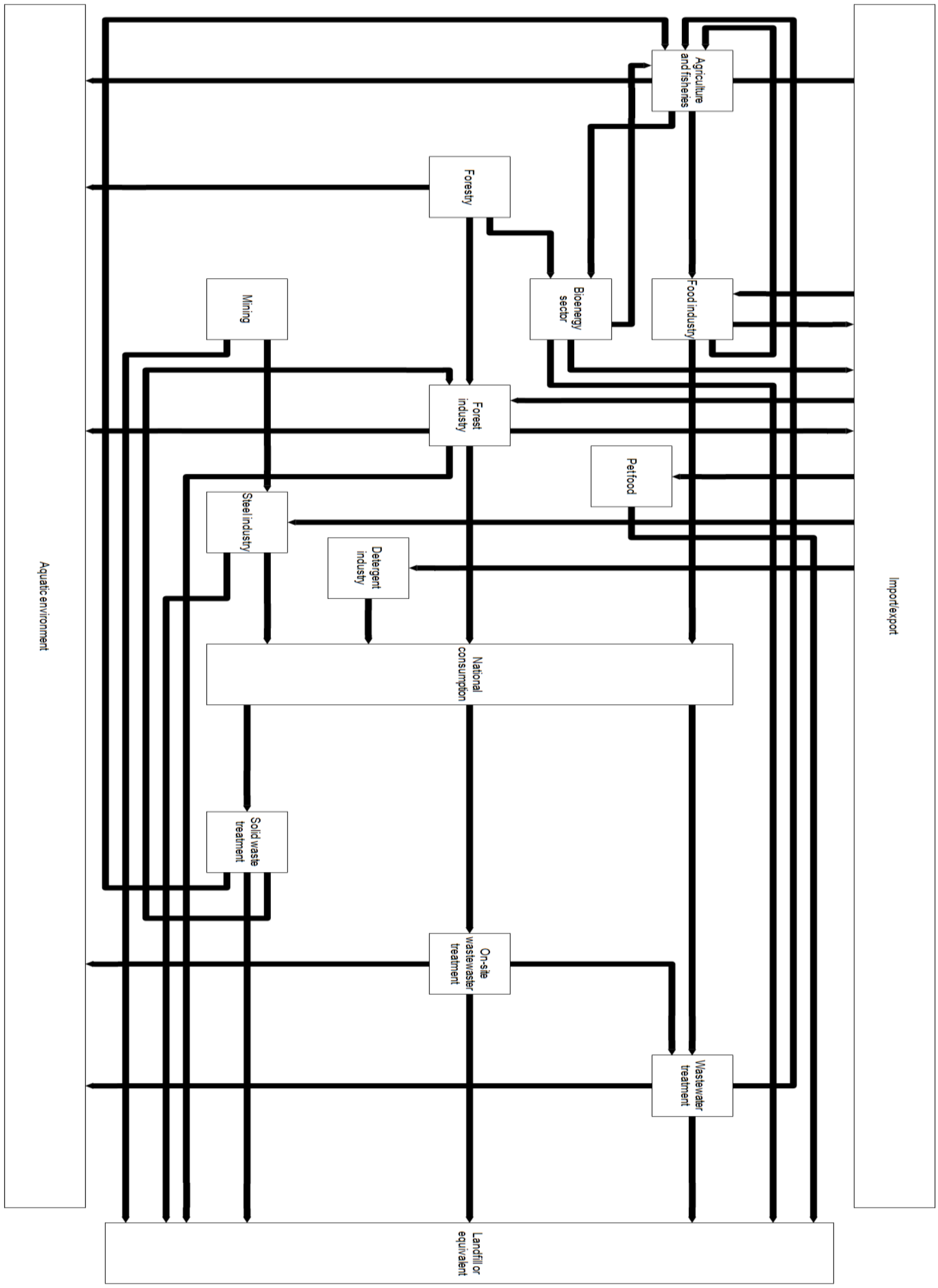

Figure 1. The conceptual model of the system.

2.2 Material flow analysis

The purpose of the first part of the study was to estimate phosphorus flows for Sweden with as little bias and ambiguity as possible. The conceptual model in Figure 1 constituted the system for which the MFA was conducted, with sectors being referred to as sub-systems. The idea behind the MFA was to create an overview of the system; analysing every sub-system or flow in minute detail is beyond the scope of this thesis.

MFA is an analytical method commonly used to calculate stocks and flows in a pre-defined system. The method is built on the law of conservation of mass, which is utilized through mass balance calculations. MFA can be carried out in different ways depending on what information is available, or what type of information or end result is desired. For this thesis, a model that only quantifies flows, and omits stocks, was chosen. Stocks and accumulation are instead discussed for selected, relevant sub-systems in section 4.4. It should also be noted that the chosen model is static, not dynamic, in the sense that it is a snapshot of the system at a certain point in time rather than a cumulative analysis which includes historical data (Brunner & Rechberger, 2004). Moreover, flows were not automatically solved for in this study. Rather, this was done when deemed necessary and sensible.

In geographical terms, the MFA was limited to the borders of Sweden, but including imports and exports of phosphorus-containing goods. As for temporal delimitations, 2017 was chosen as a reference year. To the extent that data from 2017 is available, it was acquired for this year. Since 2018 was an exceptionally warm and dry year, data from that year were avoided. Perhaps such warm years will become the norm, but so far they seem relatively rare. All flows are expressed in terms of metric tons per year.

2.2.1 Example of MFA figures

Flows of phosphorus are shown as arrows in the figures, while boxes represent processes. The figures inside the arrows indicate the size of a flow in terms of metric tons of phosphorus per year. The flow size is also indicated by the size of the arrows. This is known as a “Sankey”-style flow. All figures were made using the STAN software developed by the Vienna University of Technology.

For an example of how MFA results are illustrated in this thesis, see Figure 2. To illustrate how flows can be calculated in an MFA, let us assume that it is known that 300 tons of phosphorus enter Process 1 through Flow 1 and that 200 tons of phosphorus go on to Process 2 through Flow 2. If it is also known that Flow 3 constitutes the only other outlet from Process 1, and if it is reasonable to assume that no phosphorus is accumulated in Process 1, Flow 3 can then be calculated by subtracting Flow 2 from Flow 1. Note again, however, that flows were not automatically solved for in this way.

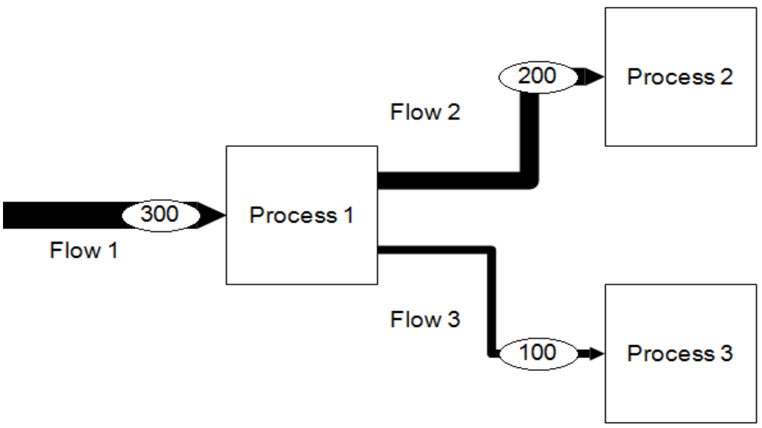

Figure 2. Example of how flows and processes are depicted in this thesis.

2.2.2 Uncertainties in the MFA

Uncertainties were handled using the framework developed by Hedbrant & Sörme (2001). This entails classifying sources based on their type and general reliability, which yields an uncertainty factor for the flow. This is the best framework for handling uncertainties in MFAs according to Danius (2002) and it is used by Egle et al. (2014) in their phosphorus balance of Austria. The idea is that rather than describing the uncertainty of a flow in terms of a uniform interval, it can be described as a factor. Thus, the interval that likely holds the true value of the flow is calculated through both multiplying and dividing the flow with its respective uncertainty factor. The specific uncertainty factors used were taken from the study by Egle et al. Since some flows are calculated using several data sources in conjunction with each other, final uncertainty factors can sometimes be a combination of several uncertainty factors. This is described further in the original article by Hedbrant and Sörme. Uncertainty factors for different flows are presented in the tables in Appendix 1.

Table 2. The methodology of the uncertainty factor concept developed by Hedbrant & Sörme (2001). Uncertainty factors for different uncertainty levels are taken from Egle et al. (2014).

Uncertainty level	Uncertainty factor	Source	Example
0	1	General value from literature	Molecular weights
1	1.11	Official statistics, appropriate scientific literature	Up to date statistics from Statistics Sweden
2	1.33	Inofficial statistics, presentations	Share of vegetable/animal waste in food waste
3	2	Publications without literature source, educated guesses	Amount of phosphorus imported in pet food

2.3 Assessment of recirculation potential

The second part of the study consisted of assessing the recirculation possibilities of different residual flows. Phosphorus flows that are either recirculated or put on landfill or equivalent were characterized based on magnitude, concentration, chemical form (e.g. iron phosphate) or plant availability, contamination and geo-spatial limitations (i.e. if the flow is found in remote places or geographically scattered to the point that utilization is hindered). For the complete reasoning behind this characterization of the different flows, see Appendix 3. While the potential separation of phosphorus from mining waste might bear more resemblance to extraction of fossil material than a recycling process, it was still treated as recirculation in this study. The phosphorus-containing ore has already been excavated, and the phosphorus is currently landfilled as mining waste in large water reservoirs. As such, utilization of the phosphorus could be regarded as a form of recirculation.

Technologies for separation of phosphorus from wastewater sludge were also briefly evaluated with respect to their recovery rates and the plant availability of the products. This was done in the light of potential upcoming legislation, which could make such technologies mandatory in Sweden.

Lastly, the recirculation potential of the national system was quantified. In this thesis recirculation is defined as utilization of residual flows in industrial biomass production, i.e. forestry or agriculture. Residual flows, in turn, are defined as flows that are currently lost from the production system to water bodies or landfill or equivalent.

First, an assessment was made regarding how much phosphorus could be recirculated to forest land. For this assessment, only flows that originate from forestry and forest industry that end up on landfill or equivalent were considered. These flows were termed “LF” in Equation 1 and Figure 3. This amount was then put in relation to the total amount of phosphorus leaving forest land every year, to give an indication of the recirculation potential. The recirculation potential was termed “RC”.

$$RC = LF \div Total\ output\ forest\ land \quad (1)$$

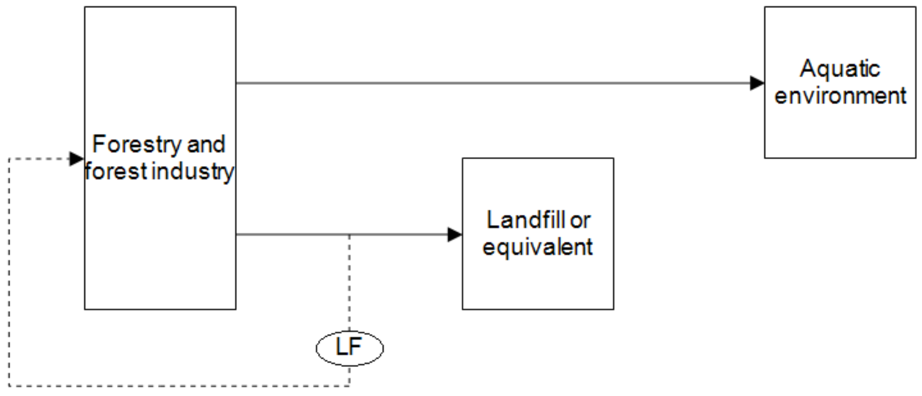

Figure 3. Recirculation to forest land. The box titled “Landfill or equivalent” includes all uses in which phosphorus is lost from the industrial production system. The flow titled “LF” is the amount of phosphorus that could potentially be recirculated from flows that are currently going to landfill or equivalent.

Three scenarios for recirculation to agricultural land were then evaluated. The flows from forest industry to landfill or equivalent were not included in these scenarios, since these were assumed to be recirculated to forest land. In the first scenario, the amount of phosphorus that can be recirculated from the waste treatment sectors, termed “$LF_{wastetreatment}$”, was quantified. The second scenario looked at the total amount of phosphorus that can be recirculated from flows that are currently landfilled, which were termed “LF”. In the third scenario, an assessment was made regarding the total recirculation potential of the system, including flows that are lost to the aquatic environment, termed “AQ”, in addition to landfill. The amount that could potentially be recirculated to agricultural land was compared to the current mineral phosphorus inputs, titled “MP”, to put the numbers into perspective, see Figure 4 and Equation 2-4. The recirculation potentials of the different scenarios for recirculation to agricultural land were titled “RC_{1-3}”.

$$RC_1 = LF_{wastetreatment} \div MP \quad (2)$$

$$RC_2 = LF \div MP \quad (3)$$

$$RC_3 = (LF + AQ) \div MP \quad (4)$$

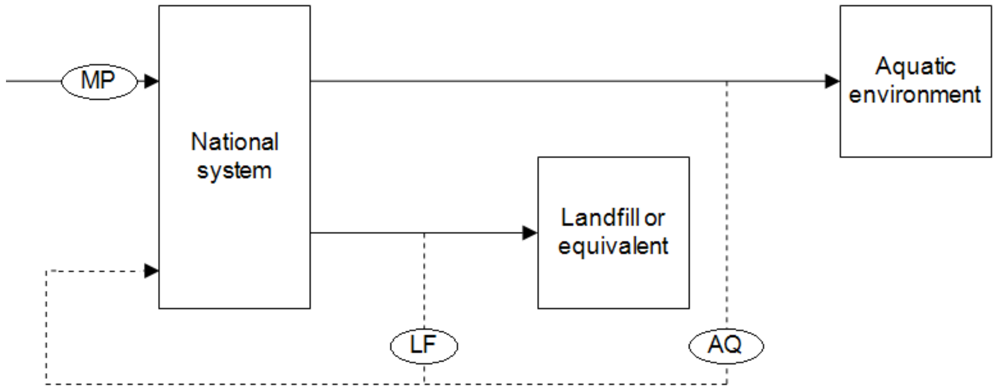

Figure 4. Recirculation to agricultural land. The box titled “Landfill or equivalent” includes all uses in which phosphorus is lost from the industrial production system. The flow titled “LF” is the amount of phosphorus that could potentially be recirculated from flows that are currently going to landfill or equivalent. “AQ” is the amount that is lost to the aquatic environment. “MP” is the current input of mineral fertilizer.

3. Results of the MFA

In this section, the results of the MFA are presented. For the calculations and data, see Appendix 2. First, the system is presented as a whole. To facilitate interpretation, results are then presented for each sub-system individually, including only flows relevant to the respective sub-system. Again, it should be noted that the boxes named “Landfill or equivalent” include uses in which phosphorus is lost from the industrial production system.

3.1 National system

The entire national system is shown in figure 5. It is evident from this figure that the phosphorus in mining waste represents a very large flow in relation to the others. It is also evident that agriculture and food production constitutes a large part of the system, with forestry and forest-related industries being slightly smaller.

In terms of recirculation opportunities, there seems to be a large potential just based on flow size data. The flows of phosphorus going to landfills or equivalent are large in relation to the flows currently being recirculated. The relevant flows and their recirculation potential are further expanded upon in section 4, “Assessment of recirculation potential”.

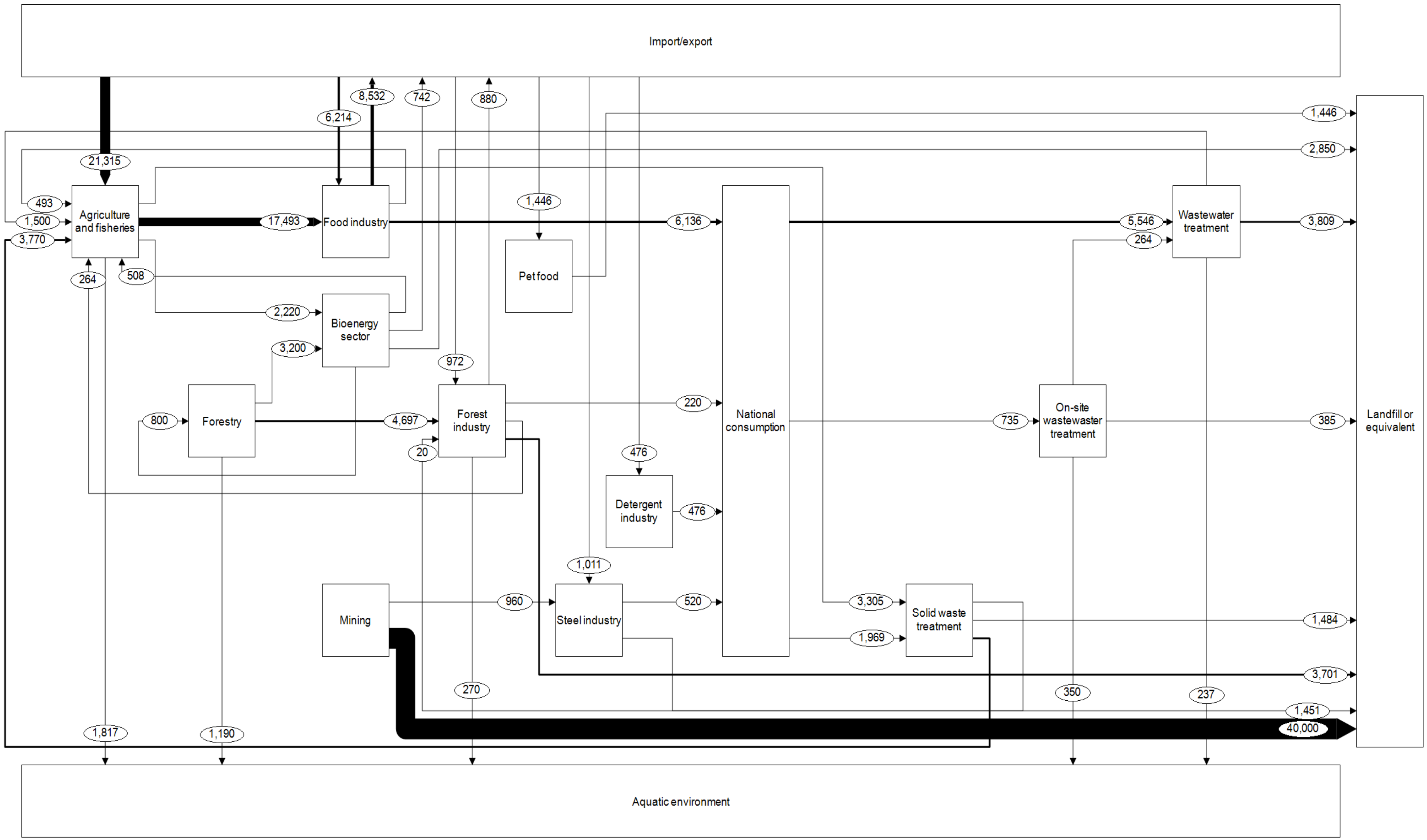

Figure 5. The phosphorus balance for the entire national system. The box titled "Landfill or equivalent" includes all uses in which phosphorus is lost from the industrial production system.

3.2 Agriculture and food production

The agriculture and food production sub-system relies heavily on an input of mineral fertilizers, which is imported from outside of Sweden. Large amounts of phosphorus are also imported in the form of animal feed. There are large internal flows of phosphorus within this sub-system, especially in the form of crops used as fodder in animal production, and manure used as fertilizer in crop production. Emissions from farmland to the aquatic environment are substantial. The largest uncertainties of this sub-system are the flows of animal products to food production, the flows of food products to national consumption, the size of the flows of animal by-products and waste from food production. The observant reader will note that the inputs of phosphorus to the "Animal production" and "Food production" boxes are significantly larger than the outputs. This may be within the realm of uncertainty of the calculations, but it may also be because some flows are missed. The uncertainty factors describe the uncertainty of the different flows, but that is not necessarily sufficient when there are missing data. Uncertainty factors only describe the data that have been found and quantified. For example, the flow "cereals to energy production" describes, as one would expect, the amount of phosphorus in cereals that goes to the energy production sector. This flow was calculated using data for the amount of cereals that go to energy production combined with a value for the phosphorus content of cereals. An uncertainty factor was assigned to this flow based on the uncertainty levels of these information sources according to the methodology described in section 2.1. However, this uncertainty does not take into account that data for other types of crops may have been missed. For instance, there may be rapeseed that is used for biofuel production for which data were not found. To avoid this type of unquantified uncertainties, more comprehensive statistics of the agricultural sector would be required.

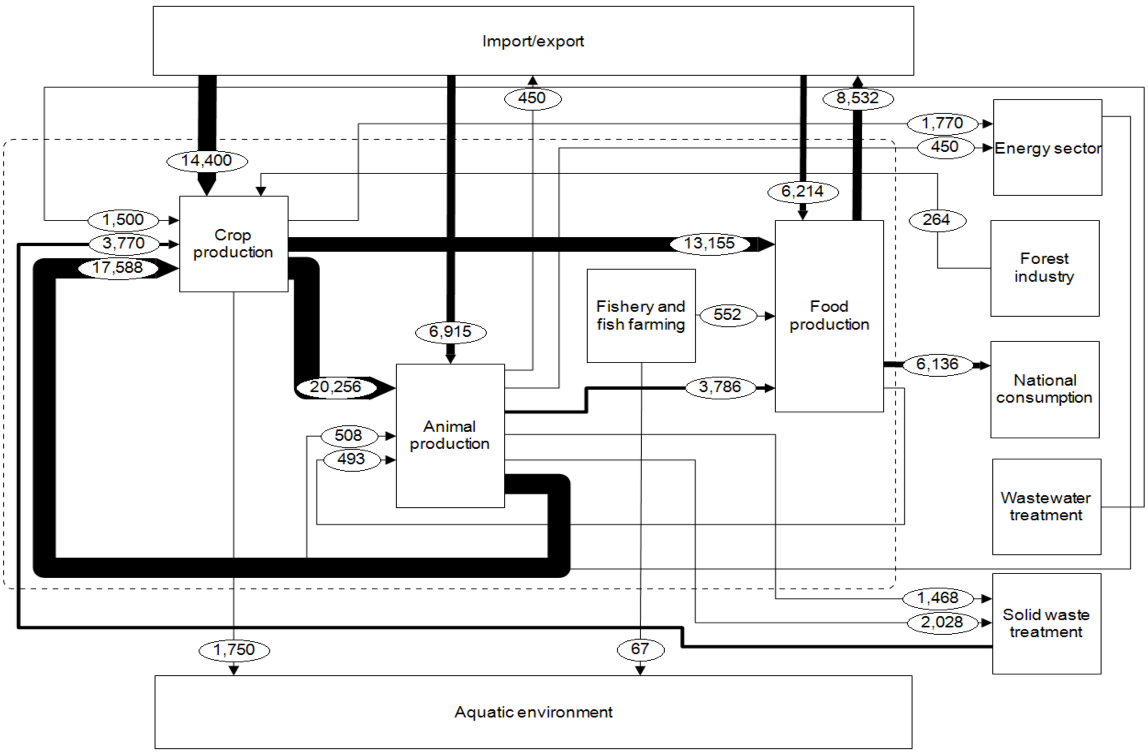

Figure 6. The agriculture and food production system. The figure only includes the flows relevant to this sub-system. The box titled "Landfill or equivalent" includes all uses in which phosphorus is lost from the industrial production system.

3.3 Pet food

Cat- and dog food seems to constitute a significant flow of phosphorus. The flows of this sub-system are relatively uncertain, since an estimation had to be made due to lack of data for pet food production.

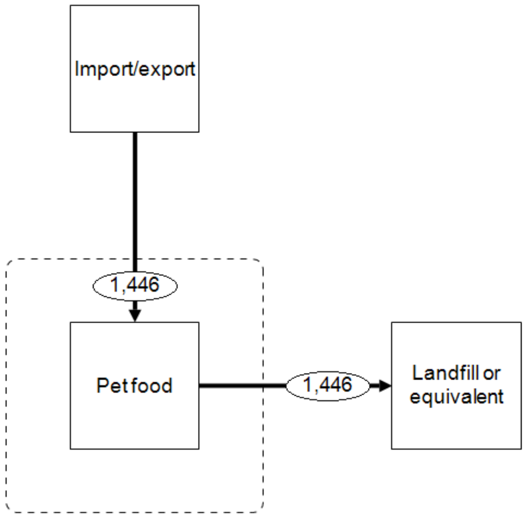

Figure 7. The pet food system. The figure only includes the flows relevant to this sub-system. The box titled "Landfill or equivalent" includes all uses in which phosphorus is lost from the industrial production system.

3.4 Forest industry

While the flows of the forest industry are not quite as large as those of the agricultural sector, they are still very significant. The feedstock of this sector consists of biomass from the forest. Only a small amount of phosphorus is applied to forest land, in the form of ashes from the burning of wood. Thus, it seems that there is a continuous depletion of nutrient reserves in Swedish forests. To some extent this may be covered by atmospheric deposition and weathering, but, as mentioned earlier, quantifying this is beyond the scope of this thesis. One might also note that out of the phosphorus going into the system, very little ends up in the products. Almost all of the phosphorus ends up in landfills in one way or another. The emissions to the aquatic environment are significant, but it should be noted that these emissions are probably harder to reduce than the emissions from agricultural lands, since the forest area in Sweden is much larger than the agricultural area.

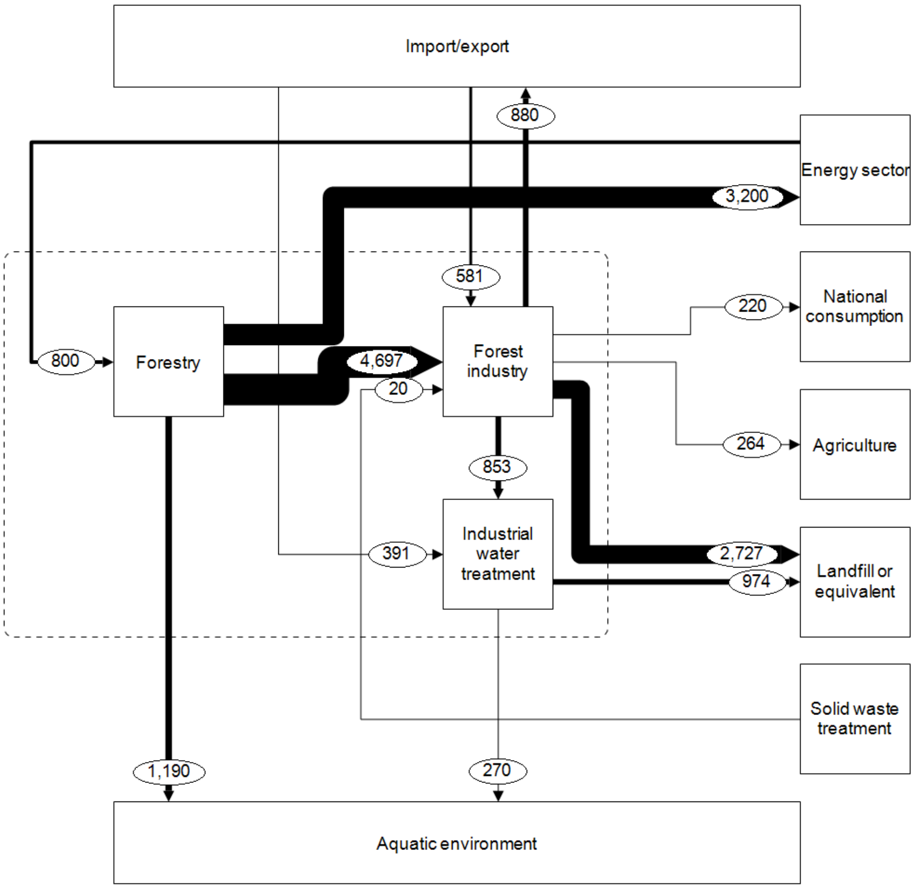

Figure 8. The forestry and forest industry sub-system. The figure only includes the flows relevant to this sub-system. The box titled "Landfill or equivalent" includes all uses in which phosphorus is lost from the industrial production system.

3.5 Mining and steel industry

As is evident from Figure 9, mining wastes represent a very large flow of phosphorus. Currently, this mining waste ends up in large water reservoirs, which basically act as a form of landfill. A significant amount of phosphorus also ends up on landfills through LD-slag, which is a residual product from the steel industry.

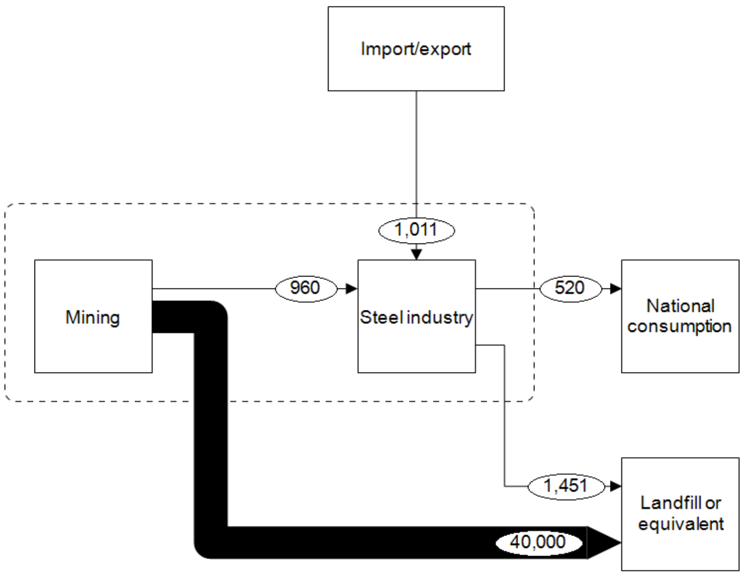

Figure 9. The mining and steel industry system. The figure only includes the flows relevant to this sub-system. The box titled "Landfill or equivalent" includes all uses in which phosphorus is lost from the industrial production system.

3.6 Chemical industry

The flows of phosphorus in the chemical industry are relatively small since there has been quite extensive legislative initiatives targeting phosphates in detergents.

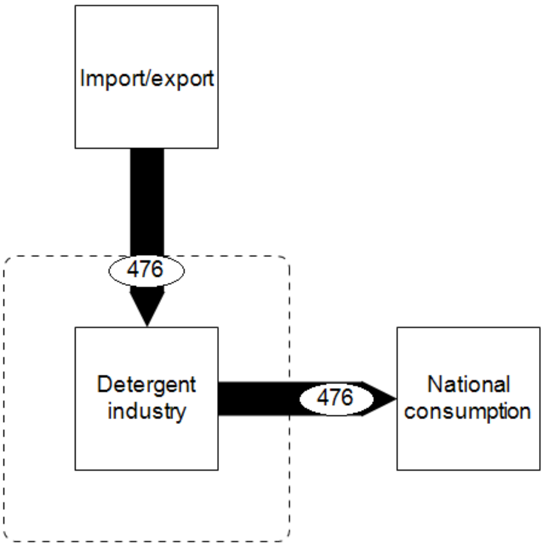

Figure 10. The chemical industry system. The figure only includes the flows relevant to this sub-system.

3.7 Bioenergy sector

Large amounts of phosphorus enter the bioenergy sector in the form of cereals, wood and animal waste. Small amounts are recirculated in the form of wood ashes and the feed product Agrodrank, and the rest either ends up as ashes in landfills or is exported.

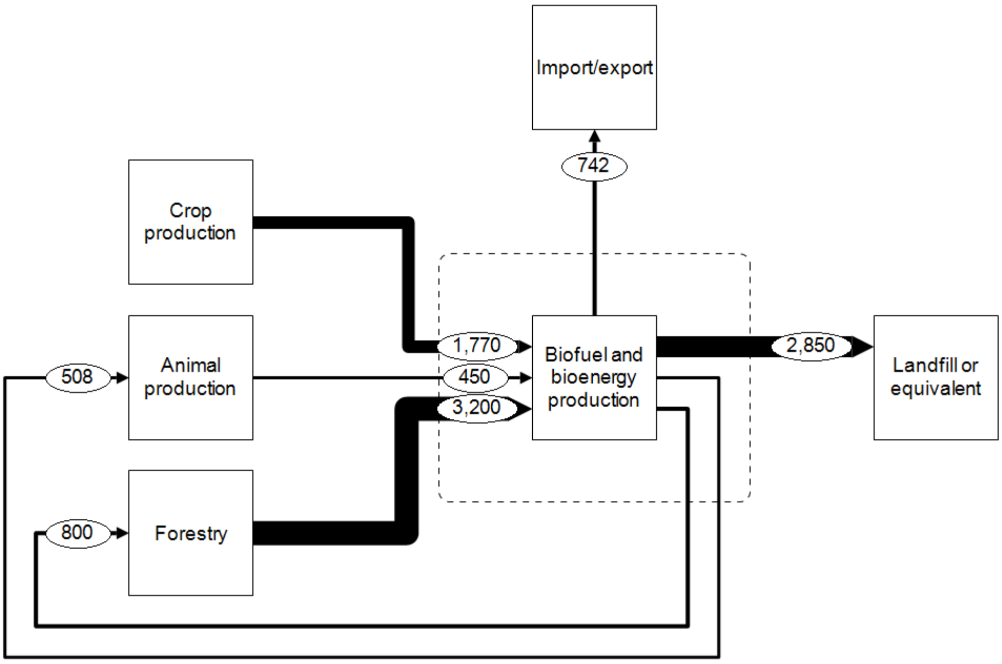

Figure 11. The bioenergy system. The figure only includes the flows relevant to this sub-system. The box titled "Landfill or equivalent" includes all uses in which phosphorus is lost from the industrial production system.

3.8 Wastewater treatment

The largest flows of phosphorus in wastewater treatment pass through the municipal wastewater treatment plants. Although the phosphorus flows that pass through on-site wastewater treatment, i.e. small, non-centralized facilities for wastewater treatment, are much smaller than those of municipal plants, the emissions to the aquatic environment are larger.

A very large share of the phosphorus in the inlet to the wastewater treatment plants ends up in sludge. Slightly more than a third of the phosphorus in the sludge is presently applied to agricultural land, and is thereby recirculated to the food production system. The rest of the sludge is either used as construction soil, for example on roadsides, as restoration material for old mines or for covering landfills. From the perspective of securing the production of food and other products, these uses have low value, and as such they were considered equivalent to landfill in this study.

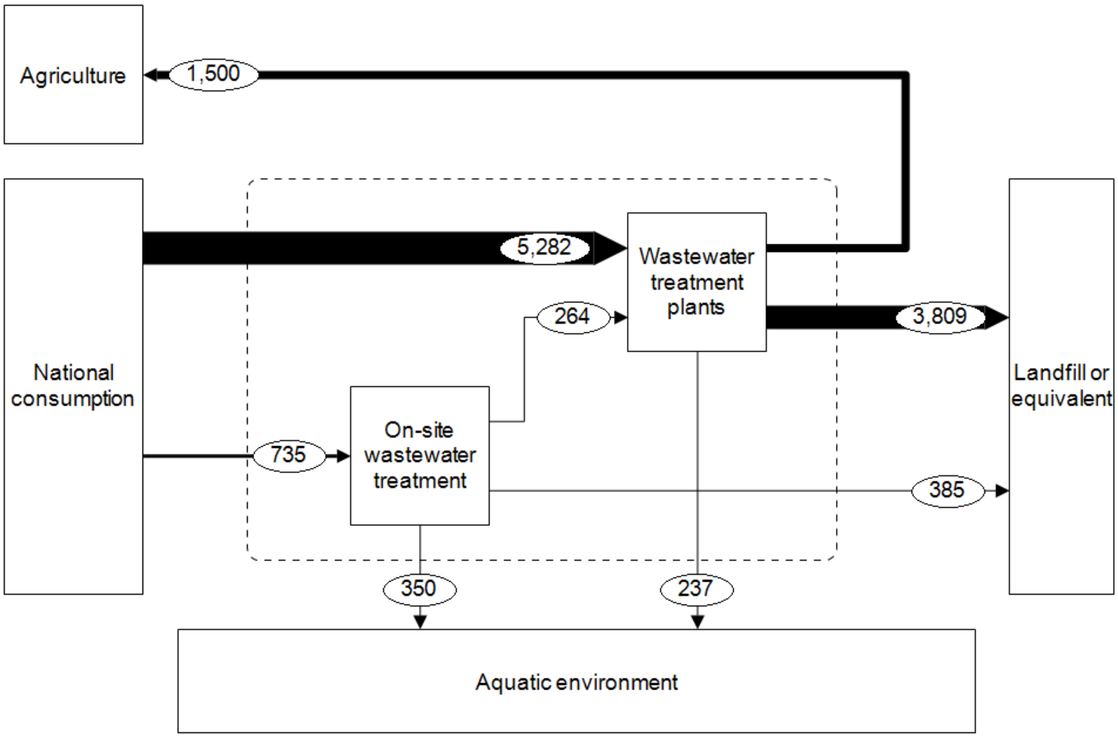

Figure 12. The wastewater treatment system. The figure only includes the flows relevant to this sub-system. The box titled "Landfill or equivalent" includes all uses in which phosphorus is lost from the industrial production system.

3.9 Solid waste treatment

There is significant recirculation of nutrients from solid waste treatment, in the form of digestates from food waste, animal by-products and manure. There is also a significant amount of phosphorus ending up in landfills from the incineration of waste. A small amount ends up in compost that is sold to household gardens. Since this is considered to leave the industrial biomass production system in this study, it was considered equivalent to landfill. A small amount of phosphorus is returned to the paper industry in the form of recycled paper waste.

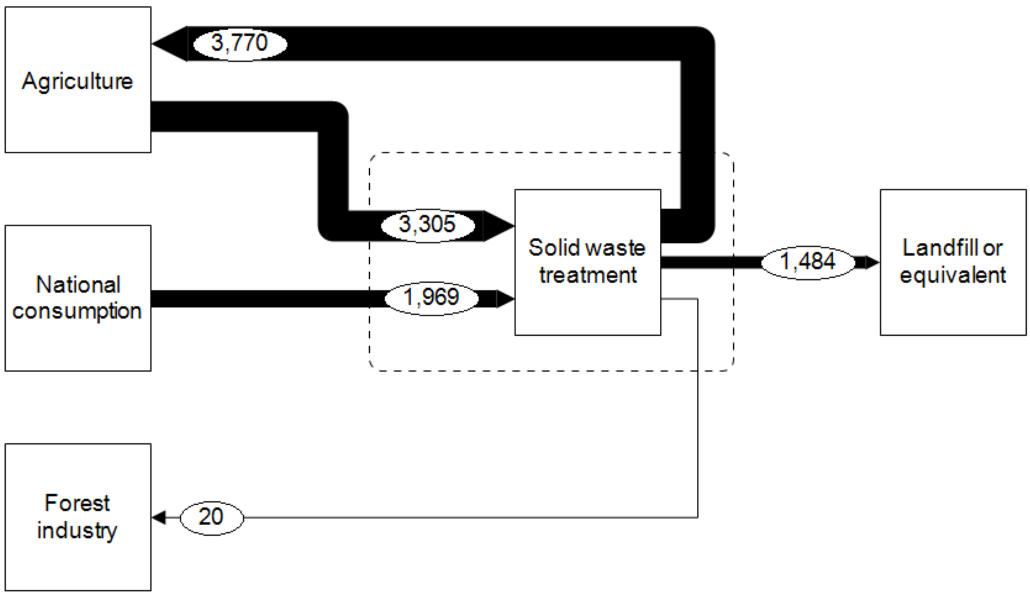

Figure 13. The solid waste treatment system. The figure only includes the flows relevant to this sub-system. The box titled "Landfill or equivalent" includes all uses in which phosphorus is lost from the industrial production system.

4. Assessment of recirculation potential

In this section, the assessment of the circularity potential is presented. First, the current level of recirculation is shown, as well as current losses to aquatic environment and landfill. Then, the recirculation potential of different residual flows is presented. The recirculation potential for wastewater treatment products was assessed in further detail in the light of recently proposed legislation. Lastly, three recirculation scenarios are discussed in order to assess the total recirculation potential.

4.1 Current situation

Phosphorus is lost from the national system either in the form of exports, flows to landfill or equivalent, or through emissions to water. Exported flows are likely utilized elsewhere, and as such are not considered as potentially recoverable losses from the production system.

4.1.1 Phosphorus losses to aquatic environment

Phosphorus emissions to the aquatic environment constitute a significant part of the total losses of phosphorus from the national system. Around 3864 tons of phosphorus are emitted to the aquatic environment from the system annually. The majority of this phosphorus comes from land runoff, while a smaller amount comes from wastewater treatment. The emissions from the different sectors to the aquatic environment are shown in Figure 14.

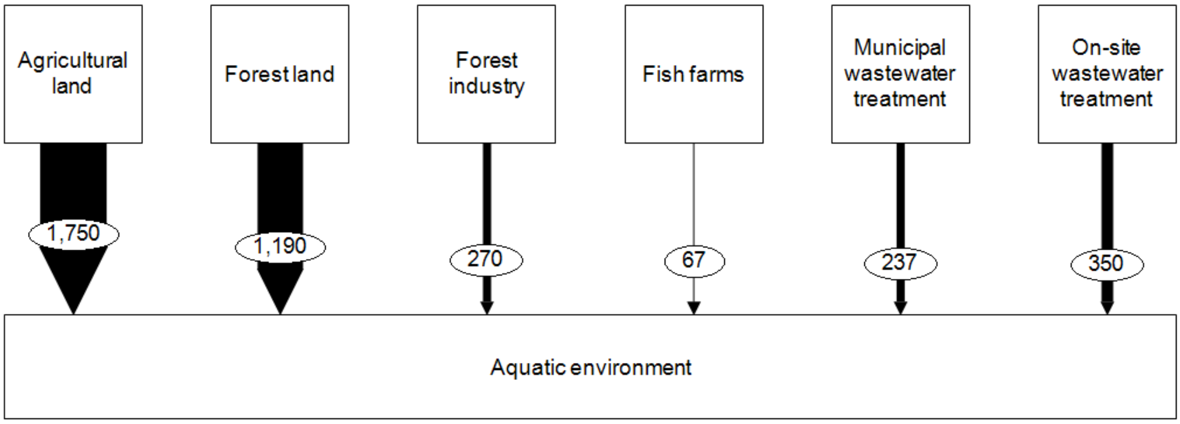

Figure 14. Emissions of phosphorus to the aquatic environment in Sweden.

There are many possible approaches to reduce these losses. Measures that increase phosphorus efficiency in agriculture are likely the most effective, since the emissions from this sector are very large in relation to emissions from other sectors. Such measures could be in the form of more rigorous enforcement of fertilizer type, amount, time of application and location according the RRRR concept (Roberts, 2007). The idea behind this concept is that nutrient emissions can be lowered while yields are kept high through more efficient nutrient management techniques. This can for example be through utilizing novel technologies for mapping out phosphorus requirements of different stretches of land in fine mesh. It could also be in the form of monitoring nutrient needs along the growing season, thus assuring an appropriate application rate of fertilizer throughout the season. Agricultural measures such as these could be very valuable as they have the potential to reduce both losses as well as demand for mineral phosphorus. Another way to reduce emissions is through trapping phosphorus from agricultural lands in filters (Ekstrand, 2017). On-site wastewater treatment seems to be another area with relatively high potential for emission abatement, since the emissions of phosphorus are much higher per capita than for municipal wastewater treatment. Phosphorus removal, however, is probably more difficult to address in on-site wastewater treatment, which is spread out over a large area, than in centralized treatment plants.

Throughout the years, phosphorus from emissions has accumulated in ocean sediments. In the Baltic sea, phosphorus fluxes to the water column are now higher from these ‘past sins’ than from land (Svanbäck & McCrackin, 2016). Several geo-engineering propositions have been made for reducing these fluxes. One such concept could involve dredging the phosphorus-rich sediments, growing algae in the sediment media, burning the algae for energy and extracting the phosphorus from the ashes. The algae could also be turned into biofuel. Such schemes, however, are not without their flaws and uncertainties. For example, it is unclear how much phosphorus would be released into the water column as a result of dredging. Dredging can also have other environmental impacts, such as affecting decomposition rates of organic matter (Graca et al., 2004). In addition, the viability of such a scheme would probably be dependent on the amount of energy that could be produced, but the energy efficiency of algae farms is not very high (Flynn, 2017). Another approach for reducing nutrient concentrations in the sea is to grow macroalgae in the water column. Such experiments have been carried out in Sweden (Soold, 2015).

4.1.2 Phosphorus losses to landfill

The majority of the losses of phosphorus from the national system end up on landfill or other uses that can be considered a waste from the perspective of industrial production. Around 53,295 tons of phosphorus are sent to landfill annually. The phosphorus in mining waste is by far the largest contributing flow, amounting to 40,000 tons per year. The flows to landfill from the different sectors are shown in Figure 15.

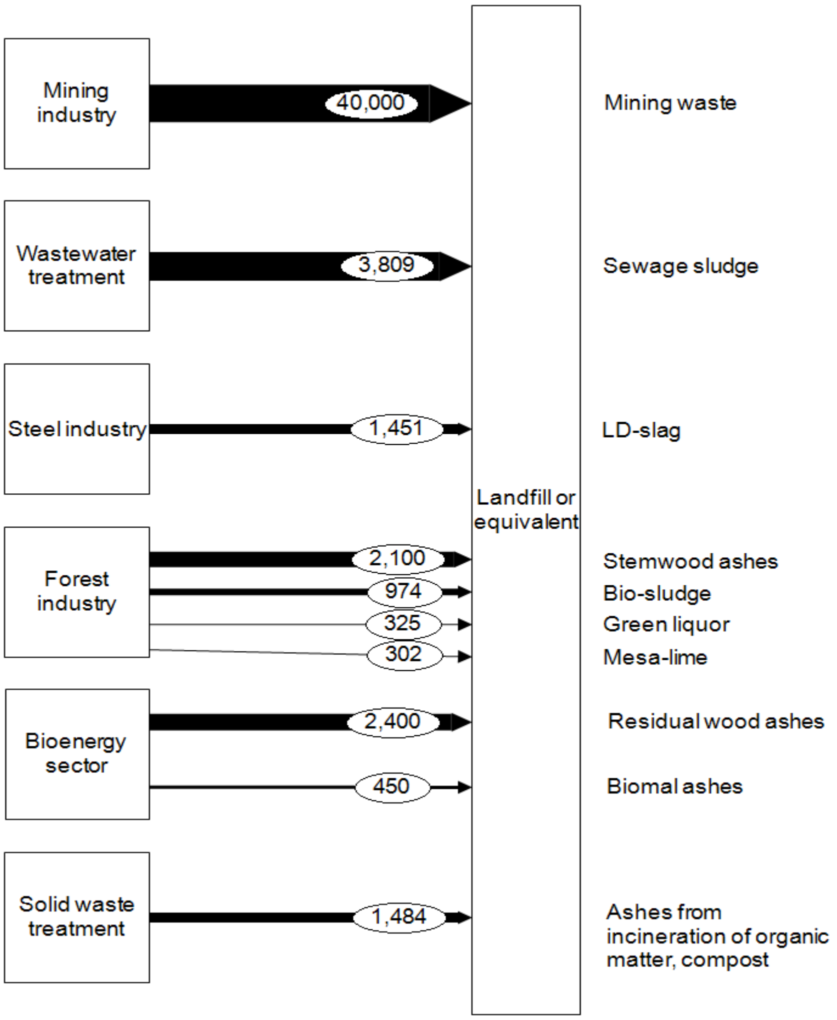

Figure 15. Phosphorus flows to landfill or equivalent. The box titled "Landfill or equivalent" includes all uses in which phosphorus is lost from the industrial production system.

Mining waste has accumulated in landfills over the years. Currently, there are around 1,500,000 tons of phosphorus in these landfills. LKAB are investigating the potential to produce phosphate fertilizer from mining waste (LKAB, 2019). However, the waste seems to be contaminated with arsenic (The Swedish geological survey, 2019).

Large amounts of phosphorus are also lost from the production system in the form of sludge from wastewater treatment. This sludge is currently used for things such as construction soil and road material (The Swedish Water and Wastewater Association, 2017). Ashes from the burning of bark from stem wood in the paper- and pulp industry, as well as ashes from the burning of tops and sticks in the bioenergy sector also represent large losses from the national system. Other losses include ashes from the incineration of food waste, wood and paper as well as compost from solid waste treatment, LD-slag from the steel industry, ashes from the burning of biological risk material (Biomal) in the bioenergy sector, as well as bio-sludge, mesa-lime and green liquor from the pulp and paper industry.

4.1.3 Currently recirculated streams of phosphorus

Recirculation of residual flows to agricultural- and forest land currently amounts to 6,862 tons of phosphorus. The Swedish forestry system is currently in a state of nutrient imbalance, with around 7,897 tons of phosphorus leaving the system in the form of wood every year and 800 tons being returned in the form of ashes. This means that only around 10% of the phosphorus that is currently removed from forest land is returned each year. To some extent, this need may be covered by rock weathering and atmospheric deposition, but this was not quantified in this thesis. Rock weathering does, however, seem to constitute a significant amount of phosphorus (Swedish University of Agricultural Sciences, 2019).

Agricultural land had an input of about 37,522 tons of phosphorus in 2017, and an output of around 35,181 tons. Uncertainties considered, agricultural land seems to be in relatively good balance in terms of input and output of phosphorus on a national scale. Of these 37,522 tons, 14,400 come from mineral fertilizer. Another 2,280 tons of mineral phosphorus are imported in the form of feed minerals to animal production. As such, Swedish agricultural production is heavily reliant on mineral phosphorus. 6,042 tons of phosphorus are recirculated to agricultural land, which is equivalent to around 41% of the total input of mineral phosphorus to agriculture.

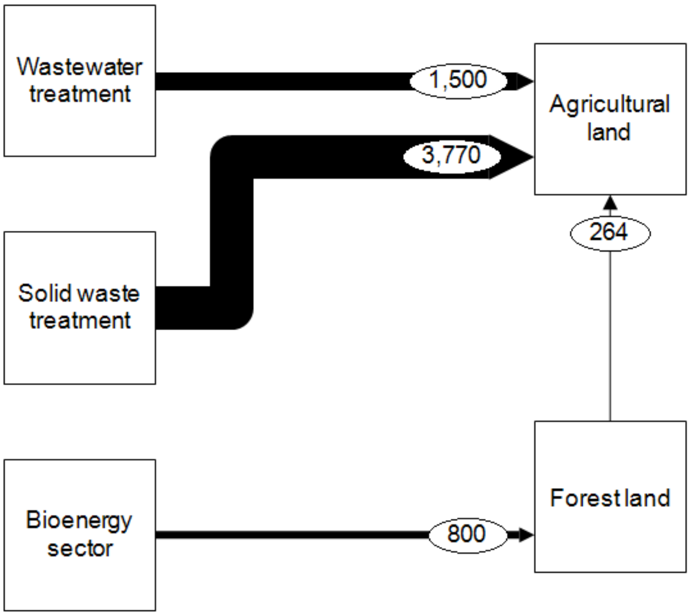

Figure 16. The flows of phosphorus that are currently recirculated to industrial biomass production.

A significant amount of phosphorus is currently recirculated to agricultural lands in the form of wastewater sludge through the REVAQ system. Relatively large amounts are also circulated to agricultural lands through digestates from solid waste treatment. However, a significant portion of the phosphorus in these digestates originates from manure. Application of manure on agricultural lands does not fall under the definition of "recirculation" used in this thesis, since practically all of it is used. This means that application of manure in agriculture is not considered recirculation unless it is first sent to a digestion facility, which may be perceived as misleading. Phosphorus is returned to forest land in the form of ashes from the burning of tops and stems. Phosphorus is also recirculated through mesa-lime to agricultural lands.

4.2 Characterization and evaluation of flows that are recirculated or sent to landfill

In this section, flows that are currently landfilled or recirculated are characterized based on magnitude, concentration, chemical form or plant availability and geo-spatial limitations. Based on the results of this characterization, the recirculation potential of the different flows is evaluated. First, a summary of the characterization, including specific numbers, is presented in Table 4. Then, the recirculation potential of each individual flow is briefly assessed. For the full reasoning behind the characterization, see Appendix 3.

Note that "geo-spatial limitation" is a measure of the extent to which utilization of a flow is hindered due to geographical scattering or remoteness. The concentration of a flow is thus taken into consideration when geo-spatial limitations are judged, since it is a large factor in whether or not these geographical disadvantages actually hinder utilization.

It should be noted that disagreements still exist over how plant availability should be judged. Plant availability of phosphorus is complex, and is dependent on things such as soil pH and soil type, among other factors (Wilfert et al., 2015). Egle et al (2016) suggest that pot and field experiments are superior to solubility tests. However, these types of studies pose an issue when it comes to the matter of time frame. Most studies are conducted over a single growing period, which may not be sufficient to evaluate the true value of a fertilizer. Additionally, slow release of phosphorus is not necessarily a disadvantage, as it may reduce runoff and lead to less eutrophication (Talboys et al., 2016). As such, in some cases, it may make sense to substitute the terminology “plant availability” of phosphorus in favour of “release rates” of phosphorus.

4.2.1 Characterization summary

In Table 4, residual flows, i.e. flows that to some extent are lost from the production system are shown along with their characteristics. The residual flows are treated in further detail in the following section.

Table 4. Residual flows, i.e. flows that to some extent are lost from the production system, that contain phosphorus and their characteristics.

Type	Sector	Magnitude (ton P/year)	Concentration (Wt% P of total)	Chemical form / plant availability	Contamination	Geo-spatial availability	Current recirculation to production sectors (%)
Mining waste	Mining and steel industry	40 000	A few	Apatite	Arsenic	Probably not an issue	0
LD-slag	Mining and steel industry	1451	0.2-0.3	Calcium phosphate	Vanadium, possibly other metals	Probably not an issue	0
Bio-sludge	Paper and pulp industry	974	0.5	Not found	Heavy metals, including cadmium	May be an issue	0
Mesa-lime	Paper and pulp industry	566	0.44	Not found	Cadmium	May be an issue	47
Green liquor	Paper and pulp industry	325	0.2-0.3	Not found	Not found	May be an issue	0
Ashes from the burning of wood	Paper and pulp industry	2100	1	Plant availability seems high	Heavy metals, cadmium in particular, radioactive elements, PAHs	May be an issue	0
Compost	Solid waste treatment	314	0.07	Plant availability seems high	Seems low	Probably not an issue	0
Digestates	Solid waste treatment	3770	0.27	Plant availability seems high	Seems low, depends on co-digested material	Probably not an issue	100 (Less for some components)
Ashes from solid waste treatment	Solid waste treatment	1174	0.013	Not found	Likely many, dependent on what other material is co-incinerated	Probably not an issue	0
Ashes from Biomal	Bioenergy production	450	3	Apatite	Biological	Probably not an issue	0
Ashes from the burning of wood	Bioenergy production	1275	0.5	Plant availability seems high	Heavy metals, cadmium in particular, radioactive elements, PAHs	May be an issue	25
Wastewater sludge	Wastewater treatment	5309	3	Aluminium phosphate or iron phosphate	Heavy metals, including cadmium	An issue	28

4.2.2 Mining waste

The flow size of phosphorus in mining waste is very large in relation to the other national flows. In addition, there are large amounts of phosphorus in the mining waste that is already landfilled. The concentration of phosphorus seems to be high. The phosphorus is in the form of apatite; fluorapatite and rare-earth element silicates (Scholz et al., 2013). This can be used to produce phosphate fertilizer, which is generally derived from apatite, and has excellent plant availability. In terms of contaminants, there seems to be arsenic present (The Swedish geological survey, 2019). This may be a large concern for producing fertilizers from mining waste. LKAB was contacted in an attempt to find out how extensive the contamination is, but no answer was received. While there may be an arsenic problem, these reserves should be relatively free from cadmium, as cadmium is present in sedimentary reserves, not igneous. As for geo-spatial limitations, the mining operations and reserves are located in the relatively remote northern parts of Sweden. However, since concentrations are high and reserves are concentrated to a few places, this should not be a major concern for potential fertilizer production, since mineral fertilizers are already shipped around the world.

4.2.3 LD-slag

LD-slag from steel production has a relatively low phosphorus concentration, but due to the large volumes produced, the total amount of phosphorus is significant. There are likely various metal contaminants present since LD-slag is a by-product from the steel industry. In particular, vanadium is present to a high degree (Hildor, 2019). Separating phosphorus from LD-slag is not only beneficial as a way to produce phosphorus fertilizer, since the LD-slag can be returned to the process if the phosphorus is removed. There are currently experiments being conducted at Chalmers University of Technology on the separation of vanadium and phosphorus from LD-slag. Marhual et al (2011) argue that phosphorus might be present as calcium phosphate, or in a calcium silica matrix. Spatial limitations should not be a large issue since slag is produced in steel factories, which operate on a relatively large scale, and phosphorus concentrations would probably be relatively high after the separation process.

4.2.4 Bio-sludge

Bio-sludge from the paper industry contains a moderate amount of phosphorus, with low to moderate concentrations. Anaerobic digestion of bio-sludge has been discussed, with the goal of producing biogas and applying digestates in agriculture, but the heavy metal contamination seems considerable. Contaminants exist in the form of copper, zink, cadmium and chromium, and very large amounts of other material would have to be co-treated in order for the digestates to reach acceptable levels of contamination (Ericsson, 2013). Geo-spatial limitations may pose a problem for agricultural applications as the phosphorus concentration is relatively low. Phosphorus would likely have to be separated first, to avoid the heavy metal problem and the transporting of large volumes of sludge. One might also envision that the industrial wastewater treatment could be done in conjunction with municipal wastewater treatment, since the two have opposite problems in terms of organic matter and nutrients. However, this is probably not really practically feasible, and the heavy metal concentrations would probably become too high for agricultural applications.

There have been processes developed that focus on phosphorus separation from bio-sludge from the paper industry. However, these processes are expensive and relatively complicated, and are not in use today (Fuglesang et al., 2015). Experiments in which the bio-sludge is processed into bio-char, which is then used as fuel, have also been conducted (Fuglesang et al., 2015).

4.2.5 Mesa-lime

Mesa-lime from the paper industry contains a fairly low amount of phosphorus, with low to moderate concentrations. It is removed from the pulp-making process because of contaminants in relation to the process. Mesa-lime seems to contain large amounts of cadmium (Hultman & Lundmark, 2007; Seefeldt, 2019). Combined with low to moderate phosphorus concentrations, that leads to a high amount of cadmium per kg phosphorus; much higher than what REVAQ allows for wastewater sludge. However, using a cadmium-to-phosphorus ratio to determine application rates may not be reasonable since mesa-lime is primarily applied to agricultural land because of its ability to amend acidic soils (The Swedish Board of Agriculture, 2018).

4.2.6 Green liquor

Green liquor constitutes a relatively low amount of phosphorus, with fairly low concentrations. No information was found regarding contaminants, but based on its phosphorus content, concentration, and geo-spatial availability, green liquor does not seem very interesting to recirculate into the industrial metabolism.

4.2.7 Ashes from the paper industry

Ashes from the forest industry constitute a relatively large amount of phosphorus, and have moderate phosphorus concentrations. These ashes mainly come from burning bark from stem wood for energy. Contaminants exist in the form of heavy metals, radioactive elements and PAHs. The cadmium content is much higher than what is allowed for agricultural purposes (Ek & Westling, 2003). Narodoslawsky & Obernberger (1996) report that the majority of the cadmium finds its way into fly ashes when combusted, leaving the bottom ashes with a lower concentration. This could potentially mean that bottom ashes could be used as a low-grade fertilizer in agriculture if mineral fertilizer is ever in short supply.

Even if the contamination might hinder usage in agriculture, these ashes can still find use in the forestry sector. According to Kiikkilä et al. (2003), spreading wood ashes rich in cadmium on forest soil has low effects on soil biota. A slow release of nutrients is preferable for the forest since its biomass growth is slow. A fast release may cause leaching of nutrients to the aquatic environment, as well as high concentrations of toxic contaminants. For that purpose, slow releasing ash granules are being developed and experimented with. In addition to the phosphorus, the ashes should contain other nutrients, such as potassium, in a similar ratio to how nutrients naturally occur in the forest.

Plant availability of phosphorus in ashes from wood seems high, with experiments by Li et al. showing phosphorus availability comparable to mineral fertilizer, but noting that further studies are needed on phosphorus availability in ash (Li et al., 2016).

4.2.8 Compost

Compost is made from mixed food waste, vegetable food waste and manure. It contains a relatively low amount of phosphorus, and the concentrations of phosphorus are low. In terms of plant availability, according to Bernstad & la Cour Jansen (2011), phosphorus in compost has a 1:1 substitution ratio when compared to mineral fertilizer. No information was found regarding contaminants in compost. Compost is not currently recirculated to industrial production sectors. Instead, it goes to private gardens and similar uses. Even though this use is classified as equivalent to landfill in this report, gardens do demand nutrients in one form or another. Compost represents a relatively small flow of phosphorus, and as such is not currently very interesting to recirculate to agricultural lands anyway.

4.2.9 Digestates from solid waste treatment

Digestates from biogas generation constitute a relatively large amount of phosphorus, with low to moderate phosphorus concentrations. The material going into biogas production facilities consists of mixed food waste, animal by-products and animal manure. To some extent wastewater sludge is also co-digested in such biogas facilities, but that was treated separately in the calculations, and is described in section 4.2.13. According to Bernstad & la Cour Jansen (2011), phosphorus in digestates has a 1:1 substitution ratio when compared to mineral fertilizer. Digestates seem to be relatively free from contaminants. Of course, the level of contamination depends on the material that is put into the specific digestion facility, but Baky et al. (2006) report that cadmium concentrations are relatively low. Geospatial limitations do not seem significant, since most digestates are already applied on agricultural lands.

4.2.10 Ashes from solid waste treatment

Ashes in the solid waste treatment sector contain a moderate amount of phosphorus, originating from food-, paper- and wood waste. This organic waste is co-incinerated with plenty of other types of waste, which greatly dilutes the phosphorus concentration. Since a large part of the phosphorus in these ashes stems from food waste, it seems wiser to work towards having more food waste digested or composted rather than trying to separate phosphorus from the ashes. There are likely plenty of contaminants in the co-incineration material, and the presence of other material dilutes the phosphorus concentration to a point where it is no longer a valuable resource.

4.2.11 Ashes from Biomal

Biomal contains a relatively low amount of phosphorus, but the concentrations are relatively high. In terms of contaminants, Biomal is produced from animal by-products and carcasses that are classified as biological risk material. This means that ashes from incineration of Biomal are currently also classified as biological risk material, so they cannot legally be recirculated into agriculture (Virta, 2019). Phosphorus is probably present in the form of apatite, which generally has to be treated to achieve a high plant availability. Either way, Biomal ashes are not currently interesting for recirculation because of the biological risk.

4.2.12 Ashes from wood in the energy sector

A relatively large amount of phosphorus enters the energy sector in the form of wooden material that is unfit for industrial production, such as sticks and tops. This material is burned for energy, and the phosphorus ends up in ashes. Some of these ashes are spread on forest land, but most are landfilled. It is probably relatively reasonable to assume similar concentrations and levels of contamination as for ashes from the pulp and paper industry. In reality, the concentration may be slightly lower due to the lower share of bark, which has a high phosphorus content. Plant availability of phosphorus in ashes from wood seems high, with experiments by (Li et al., 2016) showing phosphorus availability comparable to mineral fertilizer, but noting that further studies are needed on phosphorus availability of ash. Spatial limitations may be an issue if combustion is performed in smaller de-centralized facilities.

4.2.13 Wastewater sludge

Wastewater sludge contains a relatively large amount of phosphorus, with high concentrations of phosphorus. Currently, a significant amount of phosphorus is recycled to agricultural land every year through sewage sludge. Contaminants exist in the form of e.g. heavy metals and pathogens. Cadmium, in particular, has been pointed out as a problem.

The plant availability of phosphorus in sewage sludge has been discussed for a long time. Phosphorus is usually precipitated with iron or aluminium in wastewater treatment plants, which creates relatively strong bonds. The plant availability is often said to be lower than for mineral fertilizer. Generally, however, such statements are based on short pot experiments, which may not be sufficient to evaluate the true plant availability over a longer timeframe. In any case, iron-phosphorus chemistry is complicated, and plant availability is dependent on many different factors such as soil pH and the presence of different organic compounds (Wilfert et al., 2015).

There are considerable geo-spatial limitations for sewage sludge, since some of the more remote wastewater treatment plants cannot reasonably transport their sludge to agricultural lands. This is especially true for northern Sweden, which has very little agricultural land in comparison to the southern parts of the country.

4.3 Phosphorus recirculation from wastewater treatment

In this section, recirculation of phosphorus from wastewater treatment is treated in further detail. This is because there is currently an investigation regarding a ban on the spreading of sewage sludge on agricultural land in Sweden. As seen in the previous section, sewage sludge currently represents one of the few ways through which phosphorus is recirculated to the production system. If a ban is passed, phosphorus will have to be separated prior to application on agricultural soil.

Several separation options are available, with varying products, costs, efficiencies and energy requirements. There is a plethora of technologies suggested in this newly emerged field. Here, only the technologies that are deemed most promising are evaluated with respect to their efficiencies and the plant availability of the products. Although some of these technologies are applied on a relatively large scale in Germany (Andrews & Lloyd, 1997), most of them are either on conceptual level or pilot scale. This makes it difficult to estimate their efficiencies. Technologies that focus on extracting phosphorus from the aqueous phase achieve between 10-40% efficiency with respect to the phosphorus in the wastewater treatment plant inlet, methods that focus on extracting phosphorus from sludge achieve 40-70% efficiency, and methods that focus on first incinerating the sludge and then extracting the phosphorus from the ashes achieve 60-85% efficiency (Egle et al., 2016).

While energy-consuming, ash recovery techniques seem to be the most efficient. However, ash recovery techniques demand relatively large flows. The suppliers of the AshDec technology, Outotec, state that only Malmö, Gothenburg, and Stockholm have large enough wastewater flows to motivate construction of an ash recovery facility (Pott, 2018). This is unless sludge from elsewhere can be transported to a central facility, which becomes a question of economic and environmental transportation costs.

One solution to the issue of sludge transportation could be to incinerate the sludge in-situ, i.e. using incineration toilets. While less energy efficient than a central incineration facility, these types of toilets have two distinct advantages. The first advantage is that they can be easily used in remote areas, with the transportation of ashes being much more efficient in terms of energy or money spent per kg phosphorus transported when comparing to transportation of sludge. The second advantage is that there is no precipitation of the phosphorus with iron or aluminium, which should be beneficial in terms on plant availability. This type of technology could be especially interesting as a replacement for current on-site techniques, where it has the potential to significantly reduce phosphorus emissions to the aquatic environment.

Another advantage of ash recovery techniques is that they could potentially be applied to other residual streams in addition to wastewater sludge. For example, perhaps the bio-sludge from the paper industry could be incinerated and treated together with sewage sludge. However, the phosphorus concentration of many of the residual flows may be too low. Ash phosphorus contents of 4-5% are a good starting point for phosphorus recovery after sludge is co-incinerated with other material (Wittgren et al., 2017).

The plant availability of sewage sludge ash seems low (Lekfeldt et al., 2016) unless the ash is further treated such as in the AshDec process, in which case products can achieve high plant availability (Egle et al., 2016).

Struvite processes are often pointed out as technologically mature alternatives for phosphorus separation. The catch is that struvite processes are unlikely to achieve efficiencies over 50-60% (Egle et al., 2016; Reijnders, 2014). Studies have shown that struvite has almost comparable plant availability to mineral fertilizer in short pot experiments (Kern et al., 2008; Talboys et al., 2016).

To sum up, technologies for separation of phosphorus from sewage sludge add another step to recirculation, and with that comes efficiency losses. However, there may be benefits in terms of plant availability. If separation technologies can make the phosphorus in currently un-utilized sewage sludge useable in agriculture, it could even increase the amount of phosphorus being recirculated to the production system.

4.4 Assessment of the total potential for circularity

In Sweden, there are two main sectors that are dependent on phosphorus: agriculture and forestry. Both of these sectors have large outputs of phosphorus, and thus require large inputs. They also have different phosphorus needs with respect to amounts and release rates, as well as different tolerance to different contaminants. In this thesis, recirculation was defined as residual flows being returned to either of these two sectors. Because the needs of agriculture and forestry are so different, they are treated separately here. First, an assessment was made regarding the total recirculation potential to forest land. Then, three scenarios for recirculation to agricultural land were evaluated. The first scenario considered the amount of phosphorus that can be recirculated from the waste treatment sectors. The second scenario looked at the total amount of phosphorus that could be recirculated from the flows that are currently landfilled. In the third and last scenario, to assess the total theoretical recirculation potential of the system, both flows that are lost to the aquatic environment as well as those to landfill were considered.

4.4.1 Recirculation to forest land

Ashes from the burning of wood seem like a natural match for recirculation to forest land, since these ashes should, in addition to the phosphorus, contain other non-volatile macro- and micronutrients in proportions that match the forest's needs. These ashes constitute around 4,500 tons of phosphorus in total for both the energy sector and the pulp and paper industry, excluding the 800 tons already being recirculated. If the bio-sludge from the paper industry could also be recirculated, that would constitute another 974 tons of phosphorus. Green liquor could potentially also be recirculated, but since both the total amount and the concentration of phosphorus is rather low, recirculating green liquor does not currently seem attractive. One could also argue that mesa-lime should be returned to the forest, but since some mesa-lime is already applied in agriculture, it was assumed that recirculation to agricultural land should be the target for the currently landfilled mesa-lime as well.

Together, bio-sludge and currently un-utilized ashes from the burning of wood make up around 5,474 tons of phosphorus. If both of these flows can be recirculated, around 80% of the phosphorus leaving forest land each year could be returned.

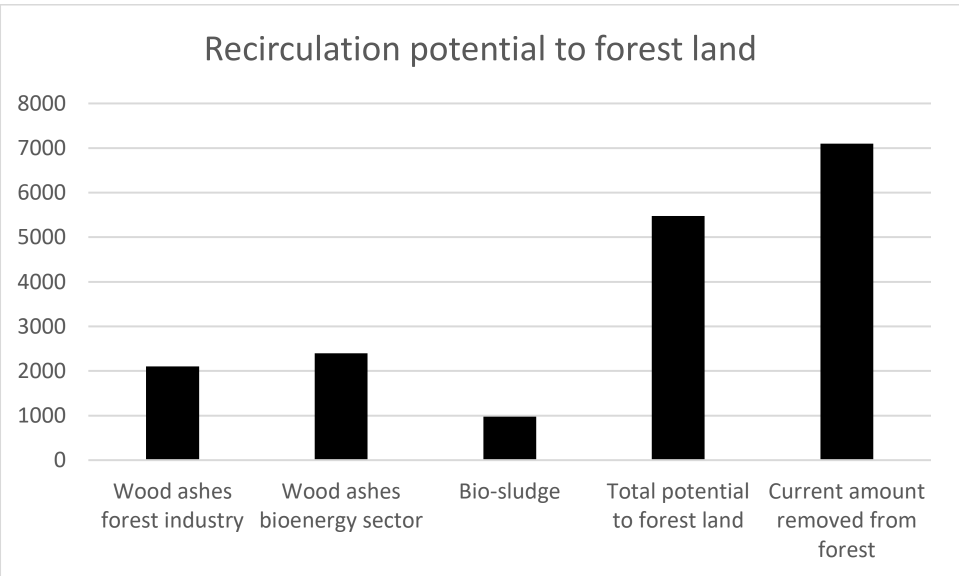

Figure 18. Recirculation potential to forest land (tons of phosphorus per year).

4.4.2 Scenario 1: Recirculation of waste treatment residuals to agriculture

For the first scenario, it is assumed that only flows that go to landfill or equivalent from the waste treatment sectors are recirculated. Phosphorus is currently recirculated from the solid waste treatment sector in the form of digestates, and in the form of sludge from the wastewater treatment sector. Since practically all digestates are already recirculated, additional phosphorus would either have to come from compost, which is currently not utilized in industrial biomass production, or from the food waste that is currently being incinerated. Compost constitutes around 313 tons of phosphorus, while the currently incinerated food waste amounts to around 1,075 tons of phosphorus. This means that the total recirculation potential from solid waste treatment is around 1,388 tons of phosphorus. For wastewater treatment, there are around 3,809 tons of phosphorus in sludge that is currently not recirculated to agriculture.

This means that the total recirculation potential from the waste treatment sectors is around 5,197 tons of phosphorus, which is equivalent to around 31% of the current input of mineral phosphorus to agricultural land.

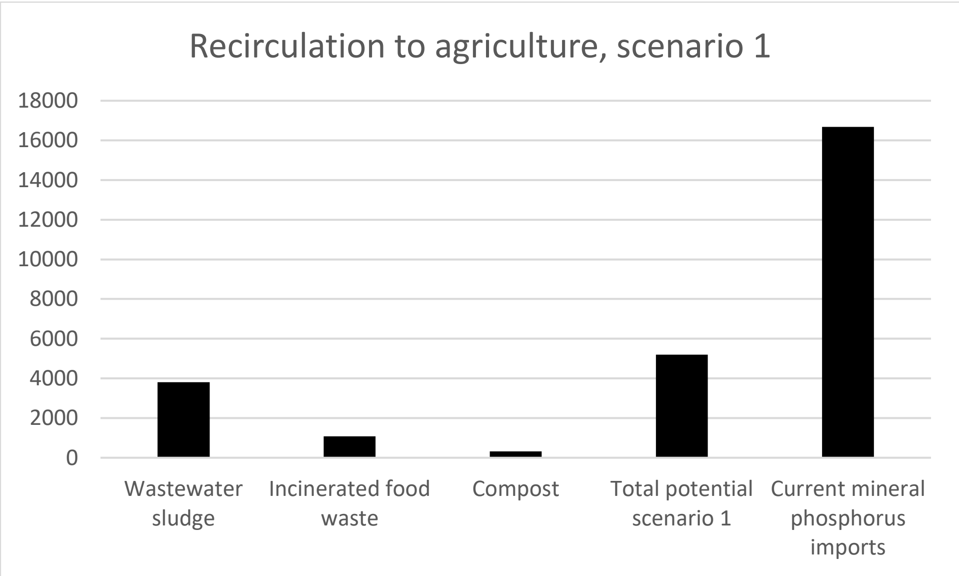

Figure 19. Recirculation potential of flows from the waste sector to agricultural land (tons of phosphorus per year).

4.4.3 Scenario 2: Recirculation of landfilled flows to agriculture

Here, it is assumed that all of the landfilled flows of phosphorus, except for those mentioned in 4.4.1, recirculation to forest land, are recirculated to agriculture. There are a couple of flows available for recirculation other than those from the waste treatment sectors discussed in section 4.4.2. There are 302 tons of phosphorus in mesa-lime which is currently landfilled, 1,451 tons of phosphorus in LD-slag, and 450 tons of phosphorus in biological risk material from the burning of Biomal. There are also 40,000 tons of phosphorus in mining waste that is currently landfilled.

Together, all of the residual flows that are currently going to landfill, except for wood ashes, bio-sludge (which are both recirculated to forest land) and mining waste, make up around 7,400 tons of phosphorus, which is equivalent to around 44% of the current input of mineral phosphorus.

If mining waste is included, it makes up around 284%.

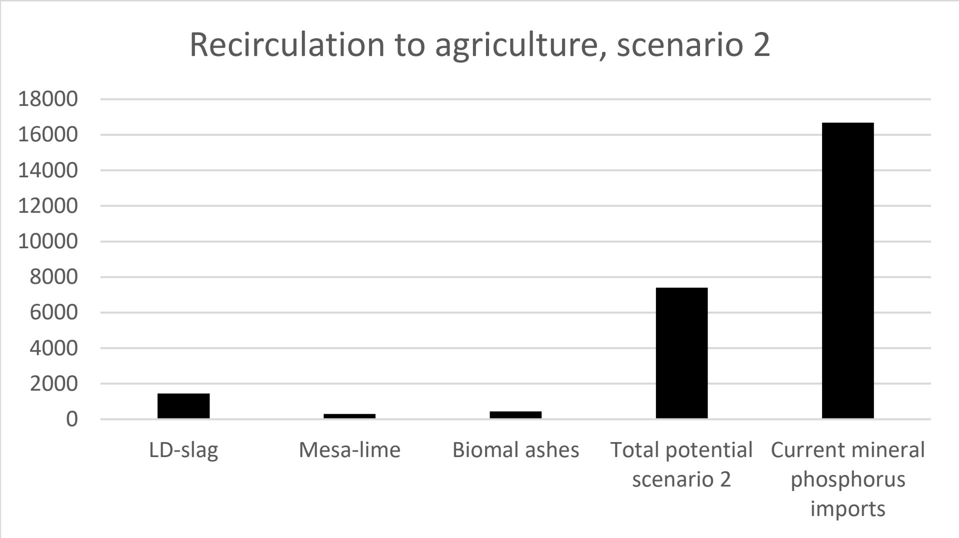

Figure 20. Recirculation potential of flows from landfilled flows to agricultural land (tons of phosphorus per year).

4.4.4 Scenario 3: Recirculation of flows lost to the aquatic environment and landfill or equivalent

In addition to the flows lost to landfill, 3,864 tons of phosphorus are lost to the aquatic environment. If it is assumed that these flows of phosphorus could be recovered, they would, together with the phosphorus in flows that go to landfill or equivalent, make up around 11,264 tons of phosphorus, or 67.5% of the current input of mineral phosphorus. If the phosphorus in mining waste was also recirculated, it would make up 307%.

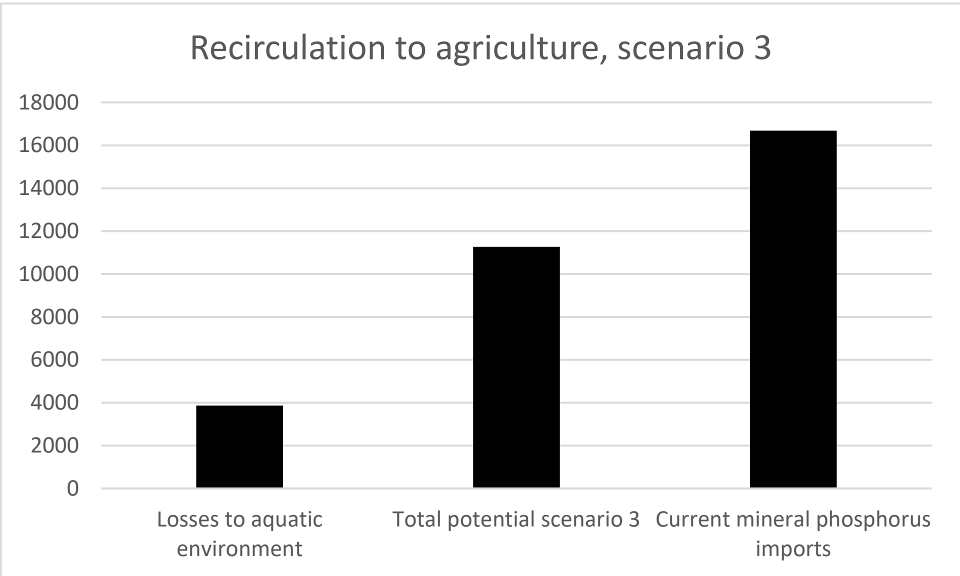

Figure 21. Recirculation potential of flows to landfill as well as flows lost to aquatic environment to agricultural land (tons of phosphorus per year).

5. Conclusions and policy recommendations

A circular economy for phosphorus in Sweden is not possible through recirculation of residual flows alone, if the phosphorus in mining waste is excluded. This is largely due to inefficiencies and losses in agriculture. Changes in agricultural practices, such as improving efficiency in fertilizer application, are required in order to decrease the dependency on mineral phosphorus.

Another way to increase phosphorus efficiency in agriculture could be to decrease animal production. Although large uncertainties still exist around phosphorus flows in Swedish agriculture, animal production requires relatively large amounts of phosphorus in the form of feed. Of course, much of the nutrients are cycled back into crop production through manure, but there are also significant losses from the system, such as through the incineration of animal by-products that are not otherwise suitable for re-use. Manure application is also much higher in areas with high animal density, which leads to an excess of phosphorus being applied (Sveriges Officiella Statistik, 2018a). As such, although agricultural land seems to be in relative balance on a national scale with respect to phosphorus, it is not in balance on local scale.

Emissions to the aquatic environment constitute a significant portion of the total phosphorus losses of the system. To achieve efficient abatement, the agricultural sector should be in focus when policies are formed.

There are large uncertainties in the agriculture and food production sectors. There are uncertainties regarding what is used as animal feed as well as what happens to animal by-products and waste from food production. As such it is very hard to pinpoint losses with high precision. In order to facilitate studies of the Swedish food chain, policies that encourage the Swedish Board of Agriculture to collect and publish more data should be made to fill these knowledge gaps.

For sewage sludge, there is a potential to utilize more than what is utilized today. If the goal is to secure future industrial biomass production, policies should be designed to ensure that sludge is either used, treated, or stored in centralized storage to facilitate future usage. Some of the uses today, such as for construction soil, are a waste from the perspective of biomass production.

Digestates are an important source of phosphorus. There is a significant potential to increase recirculation of phosphorus through increasing the amount of food waste going to digestion rather than incineration. Co-incineration of food waste with other waste potentially contaminates the ashes and dilutes the phosphorus concentration to the point where it is no longer technologically and economically feasible to recover.

Sweden is in a more or less unique situation with respect to the large amount of phosphorus-containing ashes produced by the forest industry. Policies should be formed to ensure that these are spread on forest land. Experiments with ash granules from the energy sector should be further encouraged.

Regardless of what measures are taken, Sweden is likely going to remain dependent on mineral phosphorus for the foreseeable future. In this context, it should be noted that the amount of phosphorus in mining waste is very large in relation to the other national flows. This type of mineral phosphorus cannot really be considered part of a fully circular system, but, on the other hand, the phosphorus currently circulating in the system largely stems from mineral reserves too. The phosphorus in the mining waste that is already stored in water reservoirs would be enough to sustain Sweden's needs of mineral phosphorus for around one hundred years, if the phosphorus can be extracted and made useful. As such, the phosphorus in mining waste could prove to be a valuable national resource in terms of food security. Policies should be designed to safeguard this strategic resource for use within Sweden, in case other inputs of mineral phosphorus cease.

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Appendix table of contents

Appendix 1. Results of the MFA

In this appendix, the results of the MFA are presented in table form. For a more detailed version of the calculations and data, see appendix 2.

Table 1. The agriculture and food production system.

Flow	Source	Size (ton P/year)	Uncertainty factor
Mineral fertilizer import	As reported by (Sveriges Officiella Statistik, 2018b)	14400	1.11
Animal manure used as fertilizer on agricultural lands	Calculations based on number of animals (Statistics Sweden, 2018b) combined with excretion values (Börling et al., 2018)	17588	1.35
Recycled wastewater sludge	As reported by (The Swedish Water and Wastewater Association, 2017)	1500	1.11
Recycled digestates	Calculations based on digestation feedstock statistics (Naturvårdsverket, 2016), ratio of vegetable and animal food waste and phosphorus contents of food (Bernstad et al., 2011). Digested animal by-products and manure from Energigas Sverige (Energigas Sverige, 2018)	3770	1.47
Mesa-lime from forest industry to crop production	(Seefeldt, 2019)	264	1.33
Crops to animal production	Calculations based on the amount of domestically produced compound fodder, share of cereals used as feed, silage harvests and hay harvests (Statistics Sweden, 2018b), phosphorus contents from the appendix section.	20256	1.47
Crops to food production	Calculations based on harvest statistics (Statistics Sweden, 2018b) and phosphorus contents from the appendix section.	13155	1.35
Cereals to energy production	Calculations based on the share of cereals going into energy production (SBA, 2014), phosphorus contents from the appendix section.	1770	1.47
Emissions from farmland to water	(The Swedish EPA, 2017)	1750	1.33
Imported feed to animal production	Calculations based on feed contents (Statistics Sweden, 2018b), phosphorus contents from the appendix section.	6915	2
Other inputs to animal production from food production	Calculations based on feed contents (Statistics Sweden, 2018b), phosphorus contents from the appendix section.	493	1.47
Animal products to food production	Calculated using animal production data (Statistics Sweden, 2018b), combined with phosphorus contents from the appendix section.	3786	1.47
Animal by-products to energy sector	(Virta, 2019)	450	1.33
Animal by-products to digestation	Amount of animal by-products (Energigas Sverige, 2018), assumed similar phosphorus content as those of by-products to energy sector (Virta, 2019)	2028	1.47

Animal manure to digestation	Amount of manure (Energigas Sverige, 2018), assumption that all manure is horse manure, phosphorus content of horse manure (The Swedish Board of Agriculture, 2019b)	1360	1.36
Animal manure to compost	Amount of manure (Naturvårdsverket, 2016), assumption that all manure is horse manure, phosphorus content of horse manure (The Swedish Board of Agriculture, 2019b)	108	1.36
Fish to food production	Calculations based on farm and catch statistics (Svergies Officiella Statistik, 2013; Sveriges Officiella Statistik, 2017a, 2017b), phosphorus content from the appendix section.	552	1.47
Emissions from fish farms	(The Swedish EPA, 2017)	67	1.33
Imported food products	Calculations based on import statistics (Statistics Sweden, 2018b), phosphorus contents from the appendix section.	6214	1.35
Exported food products	Calculations based on export statistics (Statistics Sweden, 2018b), phosphorus contents from the appendix section.	8532	1.35
Food products to national consumption	Calculated using consumption data (Lind, 2018), phosphorus contents from the appendix section.	6136	1.35

Table 2. The pet food system.

Flow	Source	Size (ton P/year)	Uncertainty factor
Pet food import	Solved for using the other flow, based on the assumption that all pet food is imported	1446	1.35
Phosphorus intake of cats and dogs	Calculated through the use of phosphorus intake of cats and dogs (Baker et al., 2007) in combination with the number of cats and dogs in Sweden (Agria, 2017)	1446	1.35

Table 3. The forestry and forest industry system.

Flow	Source	Size (ton P/year)	Uncertainty factor
Wood from forestry to forest industry	(Staaf, 2013)	4697	1.33
Wood from forestry to energy sector	(Staaf, 2013)	3200	1.33
Ashes returned to forestry	(Skogsstyrelsen, 2019)	800	1.33
Ashes from energy sector to landfill	Solved for using the data for wood to energy sector	3200	1.33
Emissions from forest land to aquatic environment	(The Swedish EPA, 2017)	1190	1.33
Recycled paper waste	Calculated using recycling statistics (Swedish Forest Industries Federation, 2019) in	20	1.35

	combination with phosphorus content of paper (Staaf, 2013)		
Import of biomass to forest industry	Calculated using import statistics (Swedish Forest Industries Federation, 2019), phosphorus content of wood (Staaf, 2013)	581	1.35
Exported forestry products	Calculated using export statistics (Swedish Forest Industries Federation, 2019), phosphorus content (Staaf, 2013)	880	1.35
Forestry products to national consumption	(Staaf, 2013)	220	1.11
Mesa-lime from forest industry to crop production	(Seefeldt, 2019)	264	1.33
Waste from forest industry to landfill in the form of ashes, mesa-lime and green liquor	(Staaf, 2013)	2691	1.33
Phosphorus in wastewater to industrial wastewater treatment	(Staaf, 2013)	853	1.33
Phosphorus added to wastewater treatment	(Mattsson, 2019)	391	1.33
Emissions to water from wastewater treatment	(Staaf, 2013)	270	1.33
Bio-sludge from wastewater treatment to landfill	(Staaf, 2013)	974	1.33

Table 4. The mining and steel industry system.

Flow	Source	Size (ton P/year)	Uncertainty factor
Mining waste	(The Swedish geological survey, 2019)	40000	1.11
Ore used in steel industry	(Linderholm et al., 2013)	960	1.33
Imported coal and coke used in steel industry	(Linderholm et al., 2013)	1011	1.33
Finished steel products	Calculations based on steel production numbers (Jernkontoret, 2019) and phosphorus content of steel (Sweden's Suppliers of Forging and Forged Components, 2017)	520	1.35
Slag from steel industry	Solved for using the other flows	1451	1.20

Table 5. The chemical industry system.

Flow	Source	Size (ton P/year)	Uncertainty factor
Detergents to national consumption	Estimated based on concentrations of phosphorus in greywater (Jönsson et al., 2005)	476	2
Imported detergents or phosphoric acid used to produce detergents	Solved for using the other flow	476	2

Table 6. The bioenergy system.

Flow	Source	Size (ton P/year)	Uncertainty factor
Cereals from agriculture to biofuel production	(SBA, 2014)	1770	1.47
Animal waste to produce Biomal	(Virta, 2019)	450	1.33
Wood used for bioenergy	(Staaf, 2013)	3200	1.33
Ashes returned to forestry	(Skogsstyrelsen, 2019)	800	1.33
Agrodrank used as fodder in animal production	(Linderholm et al., 2013)	508	1.33
Agrodrank exported	(Linderholm et al., 2013)	742	1.33
Ashes returned to forestry	(Skogsstyrelsen, 2019)	800	1.33
Ashes to landfill	Calculated as sum of ashes from the burning of wood and Biomal	2850	1.33

Table 7. The wastewater treatment system.

Flow	Source	Size (ton P/year)	Uncertainty factor
Municipal WWTP inlet	(Statistics Sweden, 2018a)	5282	1.11
On-site wastewater treatment inlet	Calculations based on excretion factors (Jönsson et al., 2005), and number of people using on-sites (Statistics Sweden, 2016)	735	1.35
Sludge transported from on-sites to municipal WWTP	Calculations based on technology shares and their efficiencies (Olshammar & Ericsson, 2011)	264	1.47
Phosphorus to ground filters from on-sites	Calculations based on technology shares and their efficiencies (Olshammar et al., 2011)	385	1.47
Sludge to landfill or equivalent	Solved for using the other flows	3809	1.08
Sludge recycled to agriculture	(The Swedish Water and Wastewater Association, 2017)	1500	1.11
Phosphorus to aquatic environment from municipal WWTP	(Statistics Sweden, 2018a)	237	1.11

Phosphorus to aquatic environment from on-sites	Calculations based on technology shares and their efficiencies (Olshammar et al., 2011)	350	1.47

Table 8. The solid waste treatment system.

Flow	Source	Size (ton P/year)	Uncertainty factor
Waste from national consumption	Solved for using the other flows	1969	1.29
Animal by-products and manure from agriculture	Amount of manure (Naturvårdsverket, 2016). Assumption that all manure is horse manure, phosphorus contents of horse manure (The Swedish Board of Agriculture, 2019b). Amount of animal by-products (Energigas Sverige, 2018) and assumed phosphorus content of by-products based on phosphorus content of other animal by-products (Virta, 2019)	3305	1.47
Digestates returned to agricultural land	Calculations based on digestation feedstock statistics (Energigas Sverige, 2018), assumed ratio of vegetable and animal food waste, and phosphorus contents of food waste (Bernstad et al., 2011)	3770	1.47
Phosphorus to landfill from incineration and composting of waste	Calculations based on share of food waste, paper waste and wood waste being incinerated (Naturvårdsverket, 2016) together with phosphorus contents of paper, wood and food waste (Staaf, 2013) (Bernstad et al., 2011)	1484	1.47
Recycled paper waste	Calculated using paper recycling statistics (Swedish Forest Industries Federation, 2019) and phosphorus content (Staaf, 2013)	20	1.35

Appendix 2. MFA calculations and data.

In this appendix, the MFA calculations and data are presented. For a more concise presentation of data with their respective sources, see appendix 1.

2.1 Agriculture and food production

2.1.1 Crop production

Inputs of phosphorus to crop production was assumed to consist of mineral fertilizer, animal manure, recycled wastewater sludge, and digestates from solid waste treatment. Mineral fertilizer amounted to 14400 tons for 2017 according to Statistics Sweden (Sveriges Officiella Statistik, 2018b). For wastewater sludge, the yearly REVAQ report by the Swedish Water and Wastewater Association (2017) reports that 1500 tons of phosphorus were recycled to agriculture in 2017. Compost was assumed to not be fed back to the food production industry, while digestates were assumed to be returned at a 100% rate, based on what Energigas Sverige (2018) reports. Digestates consist of food waste, animal by-products, and manure, and the calculation procedure for its phosphorus content is described in more detail in the "Solid waste treatment" section.

For harvests of different crops, data from Statistics Sweden's (2018b) yearly compilation of statistics in agriculture were coupled with phosphorus contents derived from Swedish Board of Agriculture (Börling et al., 2018), the Potash Development Association (2017) and the Swedish National Food Agency database (2017). These sources were used for all crops and food items, and are compiled in appendix 3. Total phosphorus amounted to 23828 tons for cereals, legumes, oily plants, potatoes and beets. Phosphorus in silage amounted to 9493 tons. Vegetable harvests amounted to 127 tons and 10 tons of phosphorus for outside and greenhouse harvests respectively.

Some of the cereals harvested are turned into biofuels. The share of the total harvest used for this was 12% according to a report by the Swedish Board of Agriculture (SBA, 2014), which is equivalent to 1770 tons of phosphorus. A by-product of this biofuel production is Agrodrank, a type of fodder material. This is described further in the "Bioenergy sector" section.

2.1.2 Animal production

The share of the harvest that goes into compound fodders was obtained from Statistics Sweden (2018b). The total amount of phosphorus in domestically produced compounds fodders was then calculated to 6627 tons. The amount of phosphorus from silage, 9475 tons, was based on the same report from Statistics Sweden. The share of cereals used as fodder, 41.7%, was based on SBA (2014). Then, the amount of phosphorus in fodder straw was calculated based on straw phosphorus contents obtained from Potash Development Association (2017), straw harvests which were based on cereal harvests coupled with straw to kernel ratios from a report from Nilsson & Bernesson (2009), and the share of straw used as fodder, which was based on a 2012 survey (Sveriges Officiella Statistik, 2013). The total amount of phosphorus in straw used as fodder amounted to 227 tons. The values for phosphorus in straw production are summarized in appendix 6.

The amount of phosphorus in edible animal products was calculated to 3786 tons using values for animal production from Statistics Sweden (2018b). This includes the production of cows, pigs, poultry, sheep, wild game, eggs and milk. All animals were assumed to consist of 30% waste and 70% edible contents by mass based on what the Swedish University of Agriculture states (Salomon, 2016).

Animal fertilizer production was calculated based on the number of farm animals, which was taken from the Swedish Board of Agriculture (Grönvall, 2018), and excretion data from the Swedish Board of Agriculture (Börling et al., 2018). The excretion value for horses was altered from a live weight of 500 kg to 425 kg in an attempt to correct for ponies. It should however be noted that no statistics were found for the actual number of ponies, only for horses in general. The share of manure that goes to digestation was taken from Energigas Sverige (2018), and the amount of manure that goes to compost was obtained from the Swedish EPA (Naturvårdsverket, 2016). The compost going to both digestation and compost was assumed to consist entirely of horse manure. The calculations showed that manure contains a total of 19056 tons of phosphorus, with 1360 tons going to digestation facilities and 108 tons ending up in compost.

For imports of fodder, flows were calculated based on fodder import statistics from Statistics Sweden (2018b) combined with phosphorus contents from appendix 4. Earlier, the Swedish Board of Agriculture published yearly reports on fodder contents. This is no longer the case (The Swedish Board of Agriculture, 2019a). At the moment, only the contents of fodder produced in Sweden are available, and one is left guessing as to exactly what the imported fodder contains. The quantities of the different sub-categories of feed are however still presented for imported feed. For example, the imported amount of “oily seeds and fruits” is presented. For domestically produced fodder, it is also specified that this category consists mainly of extruded rapeseed. For the imported fodder, no such specifications are made. Thus, the different sub-categories of foreign feed contents were assumed to have the same phosphorus contents as the same sub-categories of domestically produced fodder. For example, the phosphorus content of imported “oily seeds and fruits” was taken as the value for extruded rapeseed, since this is what this sub-category consists of in domestically produced compound fodder. This is likely somewhat of a misrepresentation of the foreign compound feed, since this sub-category likely consists of soybeans to a large extent. Nevertheless, it should serve as an approximation when the correct data is unavailable. The total amount of phosphorus in imported fodder was calculated to 4636 tons using this method.

Minerals in feed are only referred to by the Swedish Board of Agriculture as “minerals”, both for domestically and imported fodder. Therefore, Yara, which is the company that sells fodder minerals in Sweden, was contacted to see what type of minerals were sold. The fodder phosphates they are currently selling are monocalcium phosphate, magnesium phosphate, and monosodium phosphate, with the first one standing for the majority of their sales. The last one is marginal in comparison with the other two, and mostly goes to household pets such as cats and dogs. An estimation of the total phosphorus in feed minerals was made based on how much Yara sells. Their total sales are somewhere around 900-1000 tons per month. If 950 tons of minerals per month is assumed, and a phosphorus content of 20% is assumed, which is true for monocalcium phosphate, this amounts to 2280 tons of phosphorus per year. The phosphorus in minerals is all imported in one form or another.

Flows from fisheries and fish farms were based on professional (Sveriges Officiella Statistik, 2017a, 2017b) and recreational (Svergies Officiella Statistik, 2013) catch statistics from the Swedish Agency for Marine and Water Management as well as fish farming statistics from Statistics Sweden (2017), combined with a value for phosphorus content in fish that can be found in appendix 3. This resulted in a total of 519 tons of phosphorus from fisheries, and 33 tons of phosphorus from fish farms.

2.1.3 Animal by-products

There are uncertainties as to what happens to animal waste. The Swedish University of Agricultural Science states that around thirty percent of whole animals ends up as waste (Salomon, 2016). Linderholm et al (2013) mention that neither the Swedish Board of Agriculture nor the Swedish National Food Agency keeps record over what happens to animal by-products.

Animal waste is categorized as either category 1, 2, or 3 according to how risky it is deemed with respect to the spread of disease. The waste in category 3, which is the lowest risk class, is probably mostly treated in digestation facilities.

Much of the waste from category 1 and 2 is handled by Konvex AB, which produces a type of solid fuel called Biomal. Leo Virta on Konvex states in personal communication that they receive a total of 75000 tons of animal by-products, out of which around 50% is turned into Biomal and 50% is exported to Danish factories and turned into bone meal (Virta, 2019). This means that 37500 tons of animal by-products are turned into Biomal, which according to Virta has a moisture content of around

60% and a phosphorus content of around 3% on a dry matter basis. Thus, around 450 tons of phosphorus end up in Biomal, which is subsequently burned and turned into ashes. If it is assumed that no phosphorus is lost in the process of making Biomal, then the same quantity of phosphorus, 450 tons, is exported as animal by-products and turned into bone meal in Denmark. This would also imply that animal waste has a phosphorus content of around 1.2% in terms of wet weight.

According to Energigas Sverige (2018), 169000 tons of animal by-products are digested and turned into biogas and digestates.A similar phosphorus content as for the animal waste handled by Konvex was assumed, 1.2%, and the amount of phosphorus in this flow could then be calculated to 2028 tons. 99-100% of these digestates are applied on agricultural land (Energigas Sverige, 2018).

Gelita AB, which is a company that produces gelatine, was pointed out as a potentially large actor when it comes to animal by-products, but they could not be reached. Some animal waste might also be used for making liquid biofuels such as FAME. The Swedish Energy Agency (2017) presents data on liquid biofuel feedstock material in their publication "Energiläget", which includes animal waste products, but does not detail its origin. In addition, there is the question of pet food production, which might also be made from animal waste to some extent. This is treated further in the next section. Since there is a lack of data for these areas, the uncertainty for the animal waste flows is high.

2.1.4 Food production

Imports and exports of food products were calculated using statistics from Statistics Sweden (2018b) coupled with phosphorus contents from appendix 4. These turned out to be 6214 tons of phosphorus and 8532 tons of phosphorus respectively, including exports of cereals. The phosphorus in food consumed nationally, 6136 tons, was calculated using data from the Swedish National Food Agency (Lind, 2018) and phosphorus contents from appendix 4.

2.2 Pet food

Linderholm et al (2013) report that the Swedish Board of Agricultures statistics for animal fodder does not include food for household pets such as cats or dogs. It is, however, very unclear from the way the Swedish Board of Agriculture presents their statistics if it is included or not. Nevertheless, an estimation was made for the amount of phosphorus in the diets of cats and dogs. The method used was the same as that used by Kalmykova et al (2012).

There were 1441000 cats and 881000 dogs in Sweden in 2017 (Agria, 2017). Cats and dogs were assumed to have an average weight of 4 kg and 20 kg respectively. Dogs consume around 1.2 kg of dietary phosphorus per year (Baker et al., 2007), and if cats are assumed to require similar amounts per kg of bodyweight, they should have an intake of around 0.27 kg/year. All in all, the cat and dog food amounts to 1446 tons of P/year using this method.

It is unclear what exactly Swedish pet food is made of, since no official statistics regarding pet food contents or origins was found. The Swedish University of Agricultural Sciences states that on a European level, around half of all animal waste is made into pet food (Salomon, 2016). In Sweden, however, it appears as if most animal waste is either digested or turned into biofuels such as Biomal or possibly FAME. Therefore, it was assumed that all pet food is imported from other countries. The phosphorus in the pet food is eventually excreted, and then either left in nature or thrown in the trash. If it is thrown in the trash, it is probably incinerated. Both of these options mean that the phosphorus is removed from the industrial production of biomass.

2.3 Forest industry

Staaf (2013) investigated phosphorus flows in the forest industry in 2013. The amounts of phosphorus in wood feedstock, 5278 tons, products, 1100 tons, and waste, 3965 tons, have been obtained from this study. The share of imported feedstock, 11%, and exported products, 80%, were obtained from the Swedish Forest Industries Federation (2019).

The phosphorus in mesa-lime had to be recalculated from the study by Staaf (2013). According to Staaf, Mesa-lime contains around 900 tons of phosphorus, with a concentration of around 0.7%, varying between 0.3-1.4%. Stefan Seefeldt on Mewab, which is a company that sells mesa-lime for agricultural application, however, state in personal communication that the average concentration is around 0.44% (Seefeldt, 2019). Since this value is more up to date, and since a high phosphorus content could have been a selling point for Mewab, their lower concentration was considered more reliable. Since the flow of phosphorus stated by Staaf was calculated using the concentration, the total amount of phosphorus in mesa-lime was recalculated to 566 tons. That also meant that the total waste flow had to be recalculated from 4299 tons to 3965 tons. Mewab also stated that they sell around 60 000 tons, which is equivalent to around 264 tons of phosphorus.

The amount of phosphorus in recycled paper waste was recalculated since the number stated by the Staaf was not justified by calculations or source. Using (Staaf's (2013) value for phosphorus in paper, 0.0273 kg phosphorus per ton, along with data from the Swedish Forest Industries Federation (2019) on how much paper is recycled, 84%, the flow of recirculated paper was calculated to 20 tons.

Staaf states that 1500 tons of phosphorus is added to the wastewater treatment facilities of the paper industry, and cites Linderholm and Mattssons study as the source. Linderholm and Mattsson in turn cite personal communication with Yara. The addition of nutrients to wastewater treatment might seem odd at first glance, since municipal wastewater treatment is largely built around the removal of nutrients such as phosphorus. The wastewater from the paper industry, however, has a much higher proportion of carbon to phosphorus, and as such there is a need to add nutrients in order to feed the microorganisms that break down the organic carbon. Since this value seemed relatively high, Yara was contacted again. They replied that they sell around 1500 tons of phosphoric acid, which contains 23.7% phosphorus by weight. As such, the amount that is added to wastewater treatment in the paper and pulp industry is around 356 tons of phosphorus. Since the phosphorus content of bio-sludge that the Swedish EPA stated, 2025 tons, had been solved for using the earlier value for nutrient addition to wastewater treatment, this was recalculated to 881 tons.

2.4 Mining and steel industry

The mineral from which iron is extracted, apatite, also contains large amounts of phosphorus. Currently, this resource is not utilized, with large amounts being removed through flotation and pumped away along with process water to form landfills in the form of large water reservoirs (The Swedish geological survey, 2019)(The Swedish geological survey, 2017). Exactly how much phosphorus this constitutes is uncertain. Linderholm et al (2013) claim, citing personal communication with SSAB, that it is “in the order of one 100,000 tons per year”. Meanwhile, the Swedish geological survey (2019) states that it is around 40,000 tons per year, with reserves in water reservoirs amassing around 1,500,000 tons. Because of this large disparity, LKAB was contacted for updated numbers, but no answer was received. LKAB is also currently investigating the potential to produce fertilizer from this mining waste (LKAB, 2019).

Much of the iron mined is processed into steel. Not all phosphorus is removed in the flotation step at the extraction stage, and as such some ends up in the steel production. There is also an input of phosphorus in the form of coal and coke used, which Linderholm et al (2013) estimate to be around 1600 tons.

No official data for phosphorus concentration in finished steel products were found, but according to Sweden’s Suppliers of Forging and Forged Components (2017), the concentration of phosphorus in steel is around 0.013%, which would mean that the total amount of phosphorus in finished steel is around 520 tons, given that 4 million tons of steel are produced annually (Jernkontoret, 2019). The amount in the slag can then be solved for, which turns out to be 1451 tons.

2.5 Chemical industry

Excluding the paper and pulp industry, which is included in the section "forest industry", no official data was found regarding phosphorus usage in the chemical industry. Phosphates have traditionally been used in detergents, but with recent legislation the allowed amount has been drastically lowered. It is however still present to an extent. An estimation for the amount of phosphorus in detergents was made based on the amount of phosphorus in greywater.

Jönsson et al (2005) states that the amount in greywater is around 0.15 grams of phosphorus per person and day, which is equal to a total of 548 tons per year since Sweden has a population of around 10 million people. This amount was assumed to stem solely from detergents. Around 83% of detergents are imported (The Swedish Chemicals Agency, 2019), and the rest are produced domestically. However, since these are produced from imported phosphoric acid, all of the phosphorus in detergents is imported in one form or another.

2.6 Bioenergy sector

Sweden is heavily reliant on bioenergy. Examples of energy carriers are wood chips, pellets, biogas, and liquid fuels such as HVO and FAME. It has proven difficult to find data on production details for some of these biofuels.

Staaf (2013) states that 3200 tons of phosphorus end up in ashes from the burning of sticks and tops of trees that cannot be used in the forest industry. As stated in the "Agriculture and food production" section, the amount of phosphorus entering the bioenergy sector in the form of cereals was calculated based on a report by the Swedish Board of Agriculture (SBA, 2014), and amounts to 1770 tons. A by-product of this biofuel production is Agrodrank, a type of fodder material. According Linderholm et al (2013), 1250 tons of phosphorus ends up in Agrodrank annually. 742 tons of phosphorus are exported in the form of Agrodrank annually, while the remaining 508 tons are used as fodder domestically (Linderholm et al., 2013). The amount of phosphorus from animal by-products that ends up as the biofuel Biomal was obtained from personal communication with Konvex AB. The calculation procedure for Biomal is described in the "Animal by-products" section.

This should mean that cereals, wood and animal waste products are accounted for. There is however still the question of rapeseed, which probably contributes significantly to the production of biofuels. Energiläget (The Swedish Energy Agency, 2017) presents numbers on what is contained in different biofuels such as HVO and FAME, but the origin of specific feedstock material is not presented. This, among other things, mentions rapeseed oil and animal waste as a feedstock material. Either this material is imported, or it stems from domestic production but no sources supporting this were found. For rapeseed, most of the phosphorus is in the husks either way, which are probably used as feed for animals. Extruded rapeseed husks are included in the statistics for compound feeds, but it is unclear if these husks originate from the food production industry or the bioenergy sector.

In this report, biogas production through digestation is treated in the "Solid waste treatment" section, since a distinction had to be made. For all intents and purposes, it could just as well have been treated in this section.

2.7 Wastewater treatment

The share of people connected to municipal wastewater treatment plants is around 87% (Statistics Sweden, 2016). The incoming water to these municipal plants contains 5546 tons of phosphorus, and the outlet contains 237 tons of phosphorus (Statistics Sweden, 2018a). The amount that ends up in sewage sludge can thus be solved for, and turns out to be 5309 tons. In addition, the Swedish Water and Wastewater Association (2017) states that 1500 tons phosphorus are applied to agricultural land every year in the form of sludge. The amount of sludge not being returned to agricultural lands can then be solved for, and turns out to be 3809 tons.

The remaining 13% of Sweden's residents are not connected to municipal wastewater treatment plants. Instead, these households have on-site treatment systems. These vary with respect to what technology they utilize. The share of different technologies, as well as their efficiencies, was mapped out by SMED in 2009 (Olshammar et al., 2011). The share of different technologies was estimated by Olshammar et al (2011) through sending out questionnaires to different municipalities, and then extrapolating the data from the municipalities that answered. The efficiencies, with respect to aquatic environment, was estimated in the same report through sending out questionnaires to experts within the field. In reality, emissions to the aquatic environment are dependent on a variety of factors such as soil type and distance to waterways. However, Olshammar et al (2011) state that the values should be relatively representative for large, comprehensive studies such as this one.

The efficiencies with respect to phosphorus were thus taken from this study and compiled into one, based on the market share of the different technologies. The combined efficiency was calculated to 0.524. The phosphorus emissions to the aquatic environment from on-sites were then calculated to 350 tons using an excretion factor of 0.57 kg phosphorus per person and year (Jönsson et al., 2005). The efficiencies and market shares can be found in appendix 7. Then, the amount of phosphorus ending up in ground filters was calculated to 121 tons based on the share of technologies using such means, and finally the amount of phosphorus in the sludge from on-sites was calculated to 264 tons. All of the phosphorus from the sludge was then assumed to be transported to municipal wastewater treatment plants.

2.8 Solid waste treatment

To quantify flows of phosphorus in solid waste treatment, only organic waste was considered. Organic waste was assumed to consist of food, animal by-products, manure, vegetable waste, paper, and wood.

The Swedish EPA presents statistics on total food waste, paper waste and wood waste going into solid waste treatment. According to the Swedish EPA, 32% of food waste goes to digestation facilities, 8% goes to compost, and the remaining 60% is incinerated (Naturvårdsverket, 2016). All food waste was assumed to consist of 24% animal food waste and 76% vegetable food waste. These were assumed to have 42.9% and 23% dry content and 0.996% as well as 0.23% phosphorus content in terms of dry matter respectively. These values were obtained from (Bernstad et al's (2011) study of food waste in 2011.

According to the Swedish Forest Industries Federation (2019), around 83.8% of all paper waste is recycled. The rest was assumed to be incinerated. A phosphorus content of 0.0273 kg P/ton was assumed for all paper waste, in line with what Staaf (2013) states. All wood waste was assumed to be incinerated as well. Wood was assumed to have a phosphorus content of 0.054 kg/ton based on Staaf (2013) and a moisture content of 15% based on data from Swedish Wood (n.d.).

The phosphorus from animal by-products, 2028 tons, and manure, 1371 tons, entering digestation facilities was taken from a report from Energigas Sverige (2018). The phosphorus content of the animal by-products was assumed to be the same as the animal by-products handled by Konvex AB. The manure was assumed to come from horses, and a phosphorus content of horse manure, 15 kg phosphorus per 10 tons of manure, was obtained from the Swedish Board of Agriculture (2019b). The amounts of phosphorus in vegetable waste, 168 tons, animal manure, 108 tons, and mixed food waste, 37.2 tons, ending up in compost were calculated based on flow size data from SMED together with phosphorus contents mentioned earlier in this section.

2.9 Atmospheric deposition

Atmospheric deposition has been subject to debate for a long time. Swedish studies have used very different numbers. For example, the Swedish Board of Agriculture has used the number 0.3 kg P/hectare while the Swedish EPA has used 0.04 kg P/hectare (Linderholm et al., 2013).

A study was released in 2014 which compiled data from different studies across the globe. It concluded that regional variation in atmospheric deposition is small, and cites the median value as 0.27 kg P/hectare (Tipping et al., 2014). If this value was to be used across both forest and agricultural land, one would conclude that the deposition amounts to around 6500 tons of phosphorus on forest land, and around 800 tons of phosphorus on agricultural land.

However, this same study also states that "Whether or not a given ecosystem experiences a net gain of atmospherically deposited P depends upon its own store of P, the proximity and pools of P in ecosystems that might supply new P, and its own emissions of P to the atmosphere. Perhaps surprisingly, few, if any, determinations of ecosystem budgets include the last term.". What is referred to as atmospheric deposition is not deposition of gaseous compounds with near constant concentrations in the air, which is the case for nitrogen. Rather, it is in the form of dust or aerosols being blown by the wind from one reservoir to another. In other words, the phosphorus has to originate somewhere. Since this thesis focuses on a relatively large area in the form of Sweden as a nation, it is probably reasonable to assume that the net balance of atmospheric deposition is more or less zero on a country level. That is not to say that it is not important. There are likely significant flows from heavily fertilized agricultural land to forest land, especially in the extensively farmed regions of southern Sweden. However, to attempt to map these flows is beyond the scope of this thesis, and as such atmospheric deposition is neither included in the MFA, nor treated further in this report.

Appendix 3. Assessment of the recirculation potential of different streams.
In this appendix, the assessment of the recirculation potential of different streams is described in detail. For a less detailed, more concise version, see table 10 in the report.

3.1 Mining and steel products

3.1.1 Mining waste

The flow size of phosphorus in mining waste is very large in relation to the other national flows, at 40,000 tons per year. In addition, there are around 1,500,000 tons in water reservoirs. The concentration of phosphorus seems to be high, “a few percent” in the ore according to the Swedish geological survey (The Swedish geological survey, 2019). The phosphorus is in the form of apatite; fluorapatite and rare-earth element silicates (Scholz et al., 2013). This can be used to produce phosphate fertilizer, which is generally derived from apatite, and has excellent plant availability.

In terms of contaminants, there is arsenic present according to the Geological Survey of Sweden. This may be a large concern for producing fertilizers from mining waste. LKAB was contacted in an attempt to find out how extensive the contamination is, but no answer was received. While there may be an arsenic problem, these reserves should be relatively free from cadmium, as cadmium is present in sedimentary reserves, not igneous. As for geo-spatial limitations, the mining operations and reserves are located in the relatively remote northern parts of Sweden. However, since concentrations are high and reserves are concentrated to a few places, this should not be a major concern for potential fertilizer production, since mineral fertilizers are already shipped around the world.

3.1.2 LD-slag

LD-slag has a concentration of around 0.2-0.3% according to Linderholm et al (2013), and contains an estimated 1,451 tons of phosphorus in total. When the Thomas-process was used to produce steel, Thomas phosphate was used as fertilizer. The concentration of phosphorus in the slag is around ten times higher with the Thomas process, and the plant availability of Thomas-phosphate seems to be relatively high. Nevertheless, it appears unlikely that the Thomas-process is going to be reintroduced since it builds on the outdated Bessemer process.

There are likely various metal contaminants present since LD-slag is a by-product from the steel industry. Vanadium in particular is present to a high degree. Separating phosphorus from LD-slag could be beneficial not only as a way to produce phosphorus fertilizer, since the LD-slag can be returned to the process if the phosphorus and vanadium is separated. There are currently experiments being conducted on Chalmers on the separation of vanadium and phosphorus from LD-slag. These experiments are made through leaching the phosphorus from the slag using sulphuric acid (Hildor, 2019). Other methods for phosphorus separation from LD-slag exist, for example through the use of bacteria (Marhual et al., 2011). Marhual et al (2011) argue that phosphorus might be present as calcium phosphate, or in a calcium silica matrix based on analysis by scanning electron microscopy. Spatial limitations should not be a very large issue since slag is produced in steel factories, which operate on a relatively large scale, and phosphorus concentrations should hopefully be relatively high once leached.

3.2 Forest products

The forest industry suffers from some geo-spatial limitations, since the paper industry is largely located in northern Sweden, while agricultural land is largely located in southern Sweden. Phosphorus concentrations are relatively low in forestry-related flows, and the industry is scattered in several, relatively small operations. This may pose a problem for agricultural applications.

3.2.1 Bio-sludge

Bio-sludge contains around 974 tons of phosphorus, with a concentration of around 0.5%. Digestation of bio-sludge has been discussed, with the goal of application of digestates in agriculture, but the heavy metal contamination seems considerable. Contaminants exist in the form of copper, zink, cadmium and chromium when digested, and very large amounts of other material would have to be co-treated in order for the digestates to reach acceptable levels of contamination (Ericsson, 2013). Perhaps incineration coupled with heavy metal separation could be used for a combination of sewage sludge and bio-sludge, but the phosphorus concentration of the bio-sludge may be too low. Ash phosphorus contents of 4-5% are a good starting point for phosphorus recovery when sludge is co-incinerated with other material (Wittgren et al., 2017).

The geo-spatial limitations may pose a problem for agricultural applications as the phosphorus concentration is relatively low. Phosphorus would likely have to be separated first, to avoid the heavy metal problem and the transporting of sludge. One might also envision that the industrial wastewater treatment could be done in conjunction with municipal wastewater treatment, since the two have opposite problems in terms of organic matter and nutrients. However, this is probably not really practically feasible, and some specific forms of readily bio-available organic matter and nutrients are probably preferred by the respective industries.

There have been processes developed, namely the BioCon and Kambi/Krepro, processes, which focus on phosphorus separation from the bio-sludge. However, these processes are expensive and relatively complicated, and are not in use today (Fuglesang et al., 2015). Experiments in which the bio-sludge is processed into bio-char, which is then used as fuel, have also been conducted (Fuglesang et al., 2015).

3.2.2 Mesa-lime

Mesa-lime contains around 566 tons of phosphorus, with a concentration of 0.44% according to Mewab, a company that sells mesa-lime for agricultural application. According to Staaf (2013), phosphorus concentrations can vary considerably, between 0.3 and 1.4%.

Mesa-lime is removed from the process because of contaminants in relation to the process. According to Hultman et al (2007), mesa-lime contains 0.8 mg of cadmium per kg, which would translate to 181 mg of cadmium per kg phosphorus. This is quite a bit higher than the 30 mg of cadmium per kg phosphorus that REVAQ allows for sludge. According to Mewab, mesa-lime contains considerably lower amounts of cadmium than what Hultman states, at 0.16-0.5 mg per kg of mesa-lime. Even at the lower end of this interval, the cadmium to phosphorus ratio is still quite considerable at 36.5 mg cadmium per kg phosphorus. However, using a cadmium to phosphorus ratio may not be a reasonable way of counting since mesa-lime is primarily applied to agricultural land because of its ability to amend acidic soils (The Swedish Board of Agriculture, 2018).

3.2.3 Green liquor

Green liquor contains around 325 ton per year, and the concentration is around 0.2-0.3%. No information was found regarding contaminants, but based on its phosphorus content, concentration, and geo-spatial availability, green liquor does not seem very interesting to recirculate into the industrial metabolism.

3.2.4 Ashes

Ashes from the forest industry contain around 2,100 tons of phosphorus per year, with a concentration of around 1% (Staaf, 2013). These ashes mainly come from burning bark from stem wood for energy, Contaminants exist in the form of heavy metals, radioactive elements and PAHs. A study by IVL Swedish Environment Research Institute found that these ashes contain around 0.007 g of cadmium per kg (Ek et al., 2003), which is equivalent to 700 mg cadmium per kg phosphorus if the phosphorus content is around 1%. This is much higher than what is allowed for agricultural purposes.

Unless either the cadmium or the phosphorus can be separated from the ash, it is not suitable to spread on agricultural soil. Obernberger et al (1996) report that the majority of the cadmium finds its way into fly ashes when combusted, leaving the bottom ashes with a lower concentration. This could potentially mean that bottom ashes could be used as a low-grade fertilizer in agriculture if mineral fertilizer ever is in short supply.

Even if the contamination might hinder usage in agriculture, ashes can still find use in the forestry sector. The Swedish forest is continually stripped of nutrients through its system of industrial biomass production, and returning the ashes to the forest would also replenish its supply of both macro- and micronutrients, in a similar ratio to how nutrients naturally occur in the forest. According to Kiikkilä et al (2003), spreading wood ashes rich in cadmium on forest soil has low effects on soil biota. Nevertheless, a slow release of nutrients is preferable for the forest since its biomass growth is slow. A fast release may cause leaching of nutrients to the aquatic environment, as well as too high concentrations of toxic contaminants. For that purpose, slow releasing ash granules are being developed and experimented with.

Plant availability of phosphorus in ashes from wood seems high, with experiments by Li et al (2016) showing phosphorus availability comparable to mineral fertilizer, but noting that further studies are needed on phosphorus availability of ash.

3.3 Solid waste products

3.3.1 Compost

Compost is made from mixed food waste, vegetable food waste and manure, and contains around 313 tons of phosphorus, with a concentration of around 0.07%. In terms of plant availability, according to Bernstad et al (2011), phosphorus in compost has a 1:1 substitution ratio when compared to mineral fertilizer. No information was found regarding contaminants in compost.

Compost is not currently recirculated to industrial food production. Instead, it goes to private gardens and similar uses. Even though this use is classified as equivalent to landfill in the result section of this report, this use demands nutrients in one form or another. Compost also represents a relatively small flow of phosphorus, and as such is not necessarily very interesting to recirculate to agricultural lands anyway.

3.3.2 Digestates

As stated earlier, digestates from biogas production are handled as a type of solid waste treatment, although it could just as well have been treated in the bioenergy section. There are around 3770 tons of phosphorus in digestates from biogas production facilities, with a feedstock of mixed food waste, animal by-products and animal manure. The concentration is around 0.27% when phosphorus contents of food waste, animal by-products and animal manure are weighted according to their respective amounts. In terms of plant availability, according to Bernstad et al (2011), phosphorus in digestates has a 1:1 substitution ratio when compared to mineral fertilizer

Digestates seem to be relatively free from contaminants. Of course, that depends on what is used as feedstock in the digestation facility, but Baky et al (2006) report that cadmium is present at around 13.6 mg/ton digestate, which with a concentration of phosphorus of around 0.27% translates to around 5 mg of cadmium per ton phosphorus. Geospatial limitations do not seem significant, since pretty much all digestates are already applied on agricultural lands.

3.3.3 Ashes

Ashes in the solid waste treatment sector contain around 1174 tons of phosphorus, originating from food-, paper- and wood waste. This organic waste is co-incinerated with plenty of other types of waste. This means that the concentration of phosphorus is only about 0.013%.

Since 1075 of the total 1174 tons of phosphorus in these ashes stem from food waste, it seems wiser to work towards having more food waste digested or composted, rather than trying to separate phosphorus form the ashes. There are likely plenty of contaminants in the co-incineration material, and the presence of other material dilutes the phosphorus concentration to a point where it is no longer a valuable resource.

3.4 Products from the bioenergy sector

3.4.1 Ashes from Biomal

Biomal contains around 450 tons of phosphorus, with a concentration of around 3%. In terms of contaminants, there is a biological risk since Biomal is produced from classified animal by-products and carcasses. This also means that Biomal ashes are currently classified so they cannot legally be recirculated into agriculture (Virta, 2019).

As for its plant availability, generally phosphorus exists in the form of different kinds of apatite in bone and meat. Apatites generally have to be treated to achieve a high plant availability. Either way, Biomal ashes are not currently interesting for recirculation because of the biological risk.

3.4.2 Ashes from the burning of sticks and tops

Staaf (2013) states that around 3200 tons of phosphorus enter the energy sector in the form of wooden material that is unfit for industrial production, such as sticks and tops. This material is burned for energy, and the phosphorus ends up in ashes. Around 25% of these ashes are spread on forest land (Skogsstyrelsen, 2019). Assuming a similar concentration as for the ashes in the paper industry would put the phosphorus content at around 1%. It is also probably reasonable to assume that the contaminants are similar, and in that case these ashes also contain large amounts of cadmium, around 700mg cadmium per kg phosphorus.

Plant availability of phosphorus in ashes from wood seems high, with experiments by Li et al (2016) showing phosphorus availability comparable to mineral fertilizer, but noting that further studies are needed on phosphorus availability of ash. Spatial limitations may be an issue if combustion is performed in smaller de-centralized facilities.

3.5 Wastewater treatment products

3.5.1 Sludge

Currently, around 1500 tons of phosphorus are recycled to agricultural lands every year through sewage sludge, with another 1500 tons of REVAQ-certified sludge being landfilled or used in other ways. The total amount of phosphorus in sewage sludge is around 5309 tons per year, with a concentration of around 3%.

Contaminants exist in the form of heavy metals, cadmium in particular. All REVAQ certified sludge has less than 30 mg cadmium per kg phosphorus, but concentrations higher than this are common and occur even within REVAQ certified plants (The Swedish Water and Wastewater Association, 2017).

The plant availability of phosphorus in sewage sludge has been discussed for a long time. Phosphorus is usually precipitated with iron or aluminium in wastewater treatment plants, which creates relatively strong bonds. A study by Lekfeldt et al (2016) found the fertilizer efficiency of sewage sludge to be 80% in a short pot experiment, without mentioning how the phosphorus was precipitated. This was not corrected for other major nutrients, but it was argued that phosphorus was the limiting nutrient. Andriamananjara et al (2016) found that sewage sludge showed 64% plant uptake in relation to mineral fertilizer in another short pot experiment, without specifying how the phosphorus was precipitated. In yet another short pot experiment, Thompson (2016) found that sludge with a mixture of aluminium- and iron-precipitated phosphorus had 74% efficiency compared to mineral fertilizer. A long-term field study in Sweden found that sludge precipitated with iron only had around 20% efficiency compared to mineral fertilizer when other major nutrients were corrected for. This study cited a 2% efficiency when originally posted, but that has since been adjusted. There also seem to be inconsistencies in soil measuring depth, which is very important in this type of study.

In any case, iron-phosphorus chemistry is complicated, and plant availability is dependent on many different factors such as soil pH and the presence of different organic compounds (Wilfert et al., 2015). As stated in the introduction to this section, it might be wiser to talk about nutrient release rate rather than plant availability.

There are considerable geo-spatial limitations for sewage sludge, since some of the more remote wastewater treatment plants cannot reasonably transport their sludge to agricultural lands. This is especially true for northern Sweden, which has very little agricultural land in comparison with the southern parts of the country.

Appendix 4. Phosphorus contents

In this appendix, the phosphorus contents of different goods are presented. The Swedish Board of Agriculture was abbreviated SBA, Potash Development Association was abbreviated PDA, Swedish national Food Agency was abbreviated SNFA, Swedish University of Agricultural Science was abbreviated SUAS.

Table 9. Phosphorus contents of different crops.

Type	Phosphorus content (kg P/ton)	Source
Winter wheat	3.17	SBA
Spring wheat	3.17	SBA
Rye	3.4	SBA
Winter barley	3.4	SBA
Spring barley	3.4	SBA
Oats	3.4	SBA
Winter triticale	3.4	SBA
Spring triticale	3.4	SBA
Mixed cereals	3.4	SBA
Maize	0.61	PDA
Peas	3.71	SBA
Broad beans	4.8	PDA
Winter rapeseed	6	SBA
Spring rapeseed	6	SBA
Winter turnip rape	6	SBA
Spring turnip rape	6	SBA
Flax	6	SBA
Silage	2.33 (per ton TS)	SBA
Food potatoes	0.5	SBA
Starch potatoes	0.5	SBA
Sugar beets	0.4	SBA
Cauliflower	0.6	SNFA
Broccoli	0.6	SNFA
Brussel sprouts	0.6	SNFA
Dill	1.2 (taken for celery, which is in the same family as dill)	SNFA
Fennel bulbs	0.4 (taken for carrot, which is in the same family as fennel)	SNFA
Kale	0.7	SNFA
Cucumbers	0.2	SNFA
Iceberg lettuce	0.5	SNFA
Other lettuce	0.5	SNFA
Jerusalem artichokes	0.4 (taken for carrot)	SNFA
Swedes	0.4	SNFA
Maize	0.4 (taken for beans)	SNFA
Onions	0.5	SNFA
Carrots	0.4	SNFA
Parsnips	0.4 (taken for carrot)	SNFA
Parsley	0.4 (taken for carrot, which belongs to the same family as parsley)	SNFA
Pumpkins	0.2 (taken for cucumber, which belongs to the same family as pumpkins)	SNFA
Leeks	0.6	SNFA
Rhubarb	0.6	SNFA
Beetroots	0.5	SNFA
Other beets	0.5 (taken for beetroot, which belongs to the beet family)	SNFA

Red cabbage	0.6 (taken as average of white cabbage and kale)	SNFA
Celery	1.2	SNFA
Esparagus	0.4 (taken for onions)	SNFA
Spinach	0.6	SNFA
Pointed white cabbage	0.6 (taken as average of white cabbage and kale)	SNFA
Zucchini	0.2 (taken for cucumber)	SNFA
White cabbage	0.5	SNFA
Garlic	0.4 (taken for onions)	SNFA
Other cabbage	0.6 (taken as average of white cabbage and kale)	SNFA
Other vegetables	0.52 (taken as average of other vegetables)	SNFA
Cherries	0.22	SNFA
Plums	0.14	SNFA
Pears	0.01	SNFA
Apples	0.07	SNFA
Blueberries	0.2	SNFA
Raspberries	0.03	SNFA
Seaberries	0.12	SNFA
Strawberries	0.2	SNFA
Rose hip	0.11 (taken as average of other types of berries)	SNFA
Blackcurrants	0.07	SNFA
Grapes	0.01	SNFA
Other berries	0.11 (taken as average of other types of berries)	SNFA
Aubergine	0.02	SNFA
Chili	0.05	SNFA
Sprouts	0.07	SNFA
Tomatoes	0.23	SNFA
Melons	0.00	SNFA
Paprika	0.15	SNFA

Table 10. Phosphorus contents of other food items.

Type	Phosphorus content (kg P/ton)	Source
Beef	1.9	SNFA
Pork	1.78	SNFA
Lamb	1.93	SNFA
Poultry	1.79 (taken for chicken with skin on)	SNFA
Wild game	1.85 (taken for ground moose meat)	SNFA
Processed meat	1.38 (taken as average of hot dogs and ham)	SNFA
Milk, cream, yoghurt products	4.6 (taken as average of yoghurt and milk powder)	SNFA
Butter	0.03	SNFA
Ice cream	0.86	SNFA
Cheese	0.44 (taken for 28% fat hard cheese)	SNFA
Eggs	1.8	SNFA
Fish, crustaceans	2.22	SNFA
Processed fish products	0.12 (taken for fish balls)	SNFA
Cereals	3.4	SBA
Flour, grains, malt	1.11 (taken for wheat flour)	SNFA
Rice	0.13	SNFA
Baked goods	0.77 (taken for bread)	SNFA
Fresh vegetables	0.1 (taken as average of aubergine, chili, sprouts, cucumbers, tomato, melon and paprika)	SNFA

Frozen vegetables	0.1 (taken as average of aubergine, chili, sprouts, cucumbers, tomato, melon and paprika)	SNFA
Dried vegetables, roots, tubers	0.5 (taken for potatoes)	SNFA
Processed potato products	0.5 (taken for potatoes)	SNFA
Other processed vegetable products	0.1 (taken as average of aubergine, chili, sprouts, cucumbers, tomato, melon and paprika)	SNFA
Fresh fruits, berries, nuts	0.11 (taken as average of blueberries, raspberries, seaberries, strawberries, blackcurrants and grapes)	SNFA
Frozen fruits, berries	0.11 (taken as average of blueberries, raspberries, seaberries, strawberries, blackcurrants and grapes)	SNFA
Syrup, jam, marmalade	0.01 (taken as average of raspberry jam and raspberry syrup)	SNFA
Other processed fruits and berries	0.01 (taken as average of raspberry jam and raspberry syrup)	SNFA
Sugar, molasses, honey	0 (taken for sugar)	SNFA
Candy	0 (taken for jelly candy)	SNFA
Coffee	3.5 (taken for instant coffee powder)	SNFA
Chocolate, cacao products	1.73 (taken for dark chocolate, 70% cacao)	SNFA
Tea, spices	0.55 (taken as average of tea powder and cacao powder	SNFA
Soups, sauces, stocks	2.125 (taken for powdered bearnaise sauce)	SNFA
Margarine, other fats	0	SNFA
Other processed cereal products	0.77 (taken for bread)	SNFA
“Other food items”	0.66 (taken as average of other food items)	-
Hard liquor	0	SNFA
Wine	0.02 (taken as average of 14% red and 14% white wine)	SNFA
Other alcoholic beverages	0.02 (taken for beer)	SNFA
Alcohol free beverages	0.01 (taken for soda)	SNFA
Tobacco	0 (data not found)	SNFA
Oily seeds, fruits	2.55 (taken as average of hazelnuts, peanuts, sunflower seeds)	SNFA
Oils, fats	0 (taken as average of olive oil, rapeseed oil)	SNFA

Table 11. Phosphorus contents of compound fodder ingredients.

Type	Phosphorus content (kg P/ton)	Source
Cereal products and by-products	3.4	SBA
Oily seeds and fruits	11 (taken as extruded rapeseed)	SUAS
Seeds of legumes, products and by-products	3.65 (taken as average of broad beans and peas)	SUAS
Roots, tubers, products and by-products	0.25 (taken as average of sugar beet molasses and potatoes)	SNFA
Other seeds and fruits, products and by-products	2.55 (taken as average of sunflower seed, hazelnuts, peanuts)	SNFA
Silage	2.33	SBA
Other plants, products and by-products	0.1 (taken as average of aubergine, chili, sprouts, cucumbers, tomato, melon and paprika)	SNFA
Milk products	11.3 (taken for powdered whey)	SNFA
Animal products from terrestrial animals	1.7 (taken as average of pig bloodmeal, cow bloodmeal, and eggs)	SNFA
Fish and other marine animals, products and by-products	2.22 (taken as average of salmon and cod fillets)	SNFA
Minerals	200 (taken as monocalcium phosphate)	Yara
“Various products”	14 (taken for yeast)	SUAS

“Other products”	4.78 (taken as average of other products)	-

Appendix 5. Phosphorus in straw fodder

In this appendix, straw fodder data is presented. Total phosphorus in straw fodder amounts to 227.4 tons.

Type	Share of straw used as green fodder	Share of straw taken in	Share of the taken in straw that is used as fodder	Total amount of straw (1000 tons)	Phosphorus content (kg/ton) (from PDA)	Total amount of phosphorus in straw used as fodder (tons)
Winter wheat	0	0.44	0.06	1800	0.63	29.94
Spring wheat	0.02	0.37	0.11	197.1	0.79	9.45
Winter rye	0.04	0.53	0.04	110.6	0.63	4.26
Winter barley	0	0.73	0.16	70.2	0.63	5.16
Spring barley	0.03	0.4	0.16	559.5	0.79	41.55
Oats	0.04	0.34	0.16	351.7	0.79	26.23
Triticale	0	0.63	0.12	101.7	0.79	6.08
Mixed cereals	0.37	0.34	0.46	24.2	0.79	10.08
Maize	0.66	0.06	0.95	215.9	0.611 (30% DM)	94.61
Rapeseed/turnip rape	0	0.07	0.05	558.4	1.16	2.27

Appendix 6. Efficiencies of different on-site wastewater treatment technologies

In this appendix, the efficiencies of different on-site wastewater treatment technologies with respect to phosphorus and aquatic emissions are presented. Data were obtained from (Olshammar et al., 2011). The weighted on-site efficiency becomes 0.524.

Type	Share of total	Efficiency
Latrine	0.05	0.9
1-/2-chamber tank	0.06	0.15
3-chamber tank	0.12	0.15
Closed tank	0.17	0.95
Sludge separation with infiltration bed	0.55	0.45
Urine separation	0.03	0.9
Compact treatment system	0.02	0.8