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The German Phosphorus Budget as a Basis for Resource Optimization

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Affidavit

I, **STEPHANIE ZAHRER**, hereby declare

1. that I am the sole author of the present Master's Thesis, "THE GERMAN PHOSPHORUS BUDGET AS A BASIS FOR RESOURCE OPTIMIZATION", 39 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Abstract

Phosphorus is a finite resource that plays an important role in everyday life. This thesis uses current data to display phosphorus flows and sinks in Germany for the year 2015 to better analyze phosphorus consumption patterns and opportunities for resource optimization. Using Material Flow Analysis (including uncertainties) and data reconciliation performed by the software STAN, shows the magnitude of phosphorus inflow in all sectors. The results indicate an overall stock increase in phosphorus in Germany for 2015. Agriculture forms an almost closed cycle of P exchange between animal husbandry and crop farming. Already 22% of treated waste water sludge is applied in farming but the potential for recovery and reuse is much higher. Further research needs to be done on how to implement measures to reuse phosphorus on a larger scale and to achieve sustainable resource management.

Keywords: MFA, phosphorus, resource optimization, Germany, P-budget

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1. Introduction

Phosphorus (P) is a limited resource, a vital nutrient for all living species. However, overuse leads to natural hazards such as eutrophication. In the last couple of years, the phosphorus cycle was not only discussed among scientists but also policy makers realized that steps had to be taken now. Several countries investigated their P consumption patterns on national (e.g. Binder et al., 2009; Egle et al., 2014a; Gethke-Albinus, 2012) or regional (e.g. Klinglmair et al., 2015) basis or for a specific sector (Antikainen et al., 2005; Schmid Neset et al., 2008).

Most of the current studies (Binder et al., 2009; Egle et al., 2014a; Klinglmair et al., 2015) use Material Flow Analysis (MFA) or Substance Flow Analysis (SFA). In the case of analyzing P budgets, both terms can be used interchangeable.

Binder et al. (2009) analyze the Swiss P-budget for the year 2006 using SFA and five categories of uncertainty ranges accounting for the quality of data sources. They find that Switzerland is a net importer and uses phosphorus mainly in agriculture. However, there seems to be an almost closed cycle between animal production and plant production. Sewage sludge treatment offers the highest potential for recovery. In 2006 only 13% of the sewage sludge were treated and total P-losses amounted up to 80%. Most P ended up in landfills or the cement industry. These four measures were identified by Binder et al. (2009) as most promising to cut P imports by about 50%: a) use of sewage sludge ash as fertilizer, b) use of animal meal as fertilizer, c) use of animal meal as feed, and d) consequential recycling of green waste.

Egle et al. (2014a) analyze the Austrian P-budget using MFA and find that Austria does not recover P to the full potential. Most of it is landfilled or stored in agricultural soils. They see the highest recovery potential in sewage sludge, meat and bone meal. Egle et al. (2014a) use the approach by Hedbrant and Sörme (2001) to account for uncertainties as does this thesis. Based on the work of Egle et al. (2014a), Zoboli et al. (2016) use a time series of the Austrian P-budget to identify priority areas to reduce P-use and find that most potential is in waste management. Combining meat and bone meal, sewage sludge and compost could lead to a reduction by 70% of fertilizers. Import dependency could be reduced by 50% if P would be recycled.

Senthilkumar et al. (2012) analyze the French P-budget using SFA without providing uncertainties. For their analysis, they take averages over data for the years from 2002 to 2006 and show trends of P use in agriculture since 1990. They find that the most important contributor is industry followed by agriculture and households. However, due to the heterogeneity of France, they suggest to focus on a regional scale to get a better understanding of regional challenges and potentials.

Schmid Neset et al. (2008) use MFA to analyze long-term changes of P loads in food production and consumption for the city of Linköping. They find that changes over time (1870-2000) are mainly related to an increase in animal production and consumption leading to an increase of P loads in waste management, and an increase in chemical fertilizers.

Antikainen et al. (2005) analyze the Finnish food production and consumption using MFA for nitrogen (N) and phosphorus (P) for the years 1995 to 1999. They find that recovering all nutrients from municipal organic waste would only replace 17% of the necessary nutrients applied in agriculture.

Klinglmair et al. (2015) analyze the Danish P-budget using substance flow analysis and a similar approach as Binder et al. (2009) to deal with uncertainties. However, they use just one uncertainty value for each of the five categories. Klinglmair et al. (2015) find that the different land use in Denmark leads to very different P use and recover potential for the three predefined regions (urban, animal husbandry dominated and mixed) than a nationwide analysis would suggest. Their research shows that differences in economic structure and land use imply different patterns of P-consumption and might help to better understand how to optimize P usage on a local level. The highest use of P, namely agriculture, might not be in the same region as the highest recovery potential (sewage sludge from urban areas), which faces policy makers with a new challenge.

Gethke-Albinus (2012) created a first P budget for Germany analyzing output and input of P into sectors of the economy to point out different methods of P recovery and their suitability. Gethke-Albinus (2012) finds that reducing and recycling P is a key factor to reduce import dependency and sees the highest potential in biogas substrate from manure and ashes from mono-incineration of sewage sludge, reducing landfilled amounts by 32%.

The goal of this thesis is to re-evaluate data sources for Germany and provide a recent P budget in a more structured way, including uncertainties of flows to identify and display flows of P loads to better understand the system of flows and stocks in Germany. This analysis will provide support for policy making and is the basis to identify potentials in phosphorus treatment and recovery. This thesis is structured as follows. First, the relevance of phosphorus – globally and for Germany in particular – will be shown. Then, the methodological approach (MFA) used for this P-budget will be explained and the German model as well as data used will be presented. Results are provided and discussed in chapter 6 which lead to the conclusion and recommendations.

2. Phosphorus as a valuable resource

2.1 About phosphorus and its utilization

Phosphorus (P) is a chemical element in the fifth main group respectively the nitrogen group in the periodic system. It has the symbol P, the order number 15 and is found in nature by its only stabilized isotope ^{31}P. Its name derives from the ancient Greek word “φως-φόρος” (phōs-phóros) that means “light-bearing”. That is how Hennig Brand, a German pharmacist and alchemist, discovered it in 1669 when he evaporated human urine to dryness, while searching for “stone of the wise” (Ashley et al., 2011). The white phosphorus glows in the dark due to chemiluminescence by its reduction, also commonly known as phosphorescence. Elementary phosphorus is noted in its white (yellow with impurities), red and black (amorphous) and various other forms.

For the sake of the diverse forms of phosphorus, there is a big variety of the different densities and melting, as well as boiling points. For example, white phosphorus has a density of 1.82 kg / L with a melting point of 44 °C and its boiling point at 280 °C. The density of red phosphorus is about 2.35 kg / L and its melting point lays at 590 °C (under pressure); it sublimates at 417 °C (Gethke-Albinus, 2012).

Due to its extreme reactivity, white phosphorus was used to fire acceleration in matches and phosphorous bombs (Ashley et al., 2011) and, when pure, it is highly toxic, with lethal concentrations under 20 mg / kg to a human, according to ChemIDplus, US National Library of Medicine *(*query of Sept.12th 2017).

This should not be confused with phosphorus-containing compounds in the human diet. Phosphorus is also a vital nutrient and phosphorus compounds are essential for all living organisms. The cellular energy supply, best known as adenosine diphosphate (ADP) and adenosine triphosphate (ATP), partly consists of it. It also has constructional and functional roles in coding deoxy-/ribonucleic acid (DNA and RNA) eugenically and is used at the cell membranes as phospholipids to direct the hyrophile phosphate-“heads” to the aqueous medium and to cover the rest of hydrophobic fatty acids (Campbell et al., 2015). It can also be found in the mammal skeleton that is the body P-stock, which major inorganic compound is calcium phosphates, like Ca-hydroxyapatite and Ca-carbonate apatite (Schäuble, 2006).

While the German Society for Nutrition (1991) recommended a daily intake of phosphorus for an adult human in average up to 700 mg and for pregnant and nursing women with up to 800 mg, in childhood and juvenile stages of growth, amounts from 500 to 1250 mg are recommended. Some other reports also assume an average intake up to 800 mg per day for adults but also a higher daily requirement of 1 to 1.2 g of phosphorus per day (Kluthe et al., 2004; Young et al., 1997).

The daily requirement depends on many individual factors, inter alia the absorption of other essential nutrients like calcium and vitamin D play a role (Gethke-Albinus, 2012). For this reason, it is required in relatively large quantities for food production all over the world. As Gwosdz et al. report in 2006, the bulk of globally extracted rock phosphates with more than 75% is used for the production of phosphoric acid, which mainly flows into fertilizer production. The bone minerals of calcium phosphates produced from raw phosphate were used as an additive in mineral feed mixtures for animals, as a component of medical calcium drugs, also in dental care products and for the production of baking powders. Other phosphorus compounds are additions to feed lime as well as additives in cheese and food preparation.

The processed fertilizer originates from phosphoric rock through intermediate states of phosphoric acid into different kinds of mineral fertilizers like the group of straight phosphate fertilizers with simple and triple super phosphate and the group of compound fertilizers like diammonium phospahte (DAP) and NPK fertilizers with nitrogen, phosphorus, and potassium content (Lecuyer et al., 2014).

The chemical industry uses it as an additive in the production of enamel, glass and porcelain. Sodium phosphates are used in detergents production as well as in water softener, leather tanning and cement production. Further phosphorus compounds are used for the production of impregnation, flame retardant, rustproofing, stripping and metal degreasing agents. Organic compounds of phosphoric acid find their use in plastic and lacquer products. Sulfur-containing phosphorus compounds are used for the production of pesticides (Gwosdz et al., 2006).

2.2 Phosphorous resources

Mineral phosphorus is mainly found in apatite rocks, which include some calcium phosphate members like common fluorapatite (Figure 1), whereas hydroxyl- and chlorapatite are rare. In nature, phosphorus is mostly found in the form of phosphates, the chemical structures which change with pH values. Phosphates are salts and esters of ortho-phosphoric acid, as well as their condensates and phosphoric acid esters. Organic bound phosphorus is present in a huge variety of molecules in all organisms (Egle et al., 2014b).

Figure 1: Fluorapatite by Cristofono (2012); source: httpw.mindat.org/min-29229.html; Sept. 16th 2017.

However, phosphate rock is a finite and nonrenewable resource. Global resources are estimated to amount up to 300 billion tons. Its prevalence is concentrated in political unstable countries, especially Morocco with the highest export, while Algeria, Syria and Jordan playing minor roles in it, as reported by the US Geological Survey (USGS) in 2012. China, the US and Russia have raw material reserves but their consumption exceeds their reserve mining (Figure 2).

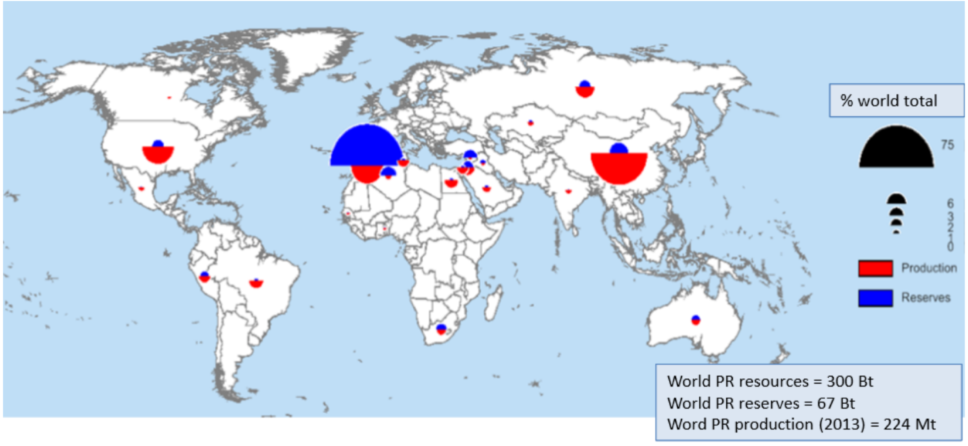
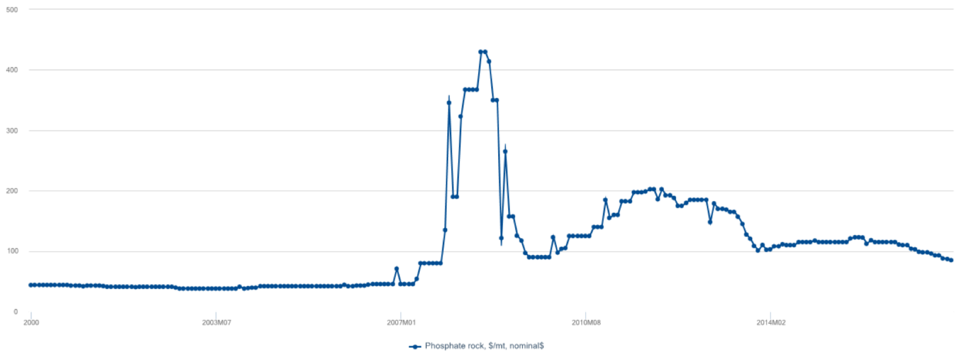


Figure 2: World reserves and production of phosphate rock by USGS in Lecuyer et al. (2014)

The awareness of the external phosphorus dependency rose, when the world markets realized in price-shock, peaking in 2008 (Figure 3). There are economic risks of affordability due to price-setting itself, but also of production shut-downs under political unstable conditions on the short- and medium-term and a general resource depletion in the long-term.

European countries are facing one of the highest risks because phosphate rock reserves are almost non-existent in Europe, so they have to import all the P minerals or P mineral fertilizers, totally dependent on the availability and world market prices (Egle et al., 2014b; Lecuyer et al., 2014).



Country : World
Source: Global Economic Monitor Commodities
Created on: 10/21/2017

Figure 3: Monthly prices of phosphate rock in nominal USD per ton between January 2000 and September 2017; Source: World Bank Group (2017) Global Economic Monitor Commodities; Oct. 21st 2017

Some ecological negative side-effects connected to phosphate rock mining is an increasing contamination of deposits with heavy metals such as cadmium (Cd) and uranium (U) for example (da Silva et al., 2010). Moreover, poor P-recycling rates are a waste of this finite resource and are also likely to lead to eutrophication of the hydrosphere (Egle et al., 2015).

The biogeochemical conversion of phosphorus takes place within the scope of the phosphorus cycle. In former times, phosphorus was recycled naturally (Ashley et al., 2011). Due to urbanization, these direct recycling circuits broke and the new fertilizing fluxes lead to economically irrecoverable depot-losses (Cordell et al., 2009; Smil, 2000). Studies on the anthropogenic P-cycle are available globally (Cordell et al., 2011; Liu et al., 2008) or on the European level (Ott and Rechberger, 2012). Measuring the P-cycle on national and regional levels may lead to the discovery of specific problems and opportunities of that country-system (Egle et al., 2014b).

2.3 Germany’s awareness about phosphorus and phosphorus cycles

The public awareness of P and its effects rose since the process of industrialization with the accompanying threat to the environment. In the early 1960s, the issue gained some political awareness (Bernadotte, 1961). When many ecosystems of inland waters had overbalanced due to eutrophication and fishing became increasingly difficult, the interest of the population increased. The phosphates of detergents in the waste water were identified (Ambühl, 1964). As the largest lake of Germany, Lake Constance, was also affected by eutrophication, it came to a turning point in politics. Count Bernadotte used his political influence and relations to set up the Green Charta (Bernadotte, 1961) and let it sign by political and economic leaders. This Charta set common targets, which aims to end environmental destruction and which general efforts in renaturation should be reached.

In the following two decades, waste water treatment was set up across Western Germany and in, a next step, renaturation of water streams in Eastern and Western Germany, especially canals, followed in the 1990s (Schilling, 1996).

Until the financial crisis in 2008 and its effect on the prices of phosphate rock, the application of phosphorus did not seem to be an issue anymore. However, the price increase following the financial crisis (Figure 3) and the resulting decrease in consumption of phosphorus fertilizers show the dependence of global agricultural production on phosphorus. And since that crisis, the focus, especially in central Europe, is targeting to recreate ecological P-cycles within the economic system on regional levels scoping the waste – and the waste water treatment. Further steps in this direction are planned in Germany, for instance, renewing the waste water treatment act (BUNB, 2017).

2.4 Germany’s policy towards P-recycling

The main legal basis for waste management on a federal level is the Recycling Act (“Law for the promotion of recycling and ensure environmentally acceptable management of waste” - “Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Bewirtschatung von Abfällen”) (BJV, 2017a) which has last been adapted in 2017.

The Recycling Act plays a key role and raised general awareness since the 1990s to use all matters in cycles. In the beginning, it was mainly focusing on the recycling of plastics, metals and glass, but lately, also nutrients like phosphorus came into focus and play an important role now. Regulated by the Water Resources Act (“Wasserhaushaltsgesetz”) (BJV, 2017b), the Waste Water Ordinance (“Abwasserverordnung”) (BJV, 2017c) and relevant state regulations, the waste water treatment plants in Germany work at the state of the art, which are “minimum requirements” at waste water treatment and the prevention of wastewater. The expansion of the treatment plants with a third stage of purification (elimination of nutrients) was compulsory through the Framework Waste Water Management Regulations of 9 November 1989, which entered into force on 1 January 1990. For the treatment of municipal waste water, the Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment[1], as amended by Regulation (EC) No 1137/2008 of the European Parliament and of the Council of 22 October 2008[2]. With this, the targeted elimination of nutrients for sensitive waters in Europe became mandatory. By the end of 1998, all municipal waste water treatment plants with a capacity of 10,000 inhabitants and larger, whose effluents had to be discharged into sensitive areas, had to be equipped with a third cleaning stage for nutrient elimination (BUNB, 2012).

In a press release of Jan. 18th, 2017, the Federal Government of Germany announced it would intensify the recycling of valuable substances from municipal waste waters and waste water sludge. Phosphorus, as a fertilizer-compound, shall be recovered. On the proposal of Federal Environment Minister, Barbara Hendricks, the Federal Cabinet adopted a corresponding amendment to the Waste Water Ordinance. On this basis, waste water treatment plants can be retrofitted to prepare them for phosphorus recycling. This technically complex process might take several years (BUNB, 2017).

The design of the Waste Water Ordinance will regulate how phosphorus can be recovered from waste waters and how pollutants can be reduced at the same time. The recast of the regulation provides that, after the expiry of appropriate transitional periods for large waste water treatment plants, phosphorus must be recovered (BUNB, 2017). Recognized but not yet implemented on a large scale, the duration of the approval procedures will have a long transition period. The duty to recover phosphorus has been, therefore, only adopted 12 years after the entry into force of the regulation for waste water treatment plants with a size of 100,000 inhabitants and 15 years after application date for plants with a size of 50,000 inhabitants or more. The regulation does not provide for a specific technology for the recovery of phosphorus but leaves space for the use or development of innovative processes. It will, thus, be possible to recover phosphorus from waste water sludge bags, directly from the sludge or generated waste water.

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[1] http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31991L0271; query Sept 26th, 2017.

[2] http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32008R1137; query Sept 26th, 2017.

Exceptions will exist only for waste water with particularly low phosphorus contents (BUNB, 2017).

2.5 Comparison to other European countries

Due to the increasing awareness of the importance of phosphorus, several P-budgets were done for different countries or regions.

For example, Austria (Egle et al., 2014a, 2014b), Denmark (Klinglmair et al., 2015), Finland (Antikainen et al., 2005), France (Senthilkumar et al., 2012), Germany (Gethke-Albinus, 2012), Sweden (Schmid Neset et al., 2008), and Switzerland (Binder et al., 2009). Their findings were already discussed in chapter 1. Most of these P-budget studies at country level “differ considerably from each other because of the different approaches and methodologies used”, as Egle et al. (2014a) consider in the Austrian P budget. A uniform calculation method according to standardized scales is important for a better comparability. For this reason, the ÖNORM S 2096 (2005) serves as a valuable template to unify the method of Material Flow Analysis (MFA), taking into account data uncertainties or intervals. In this thesis, a current P-budget for Germany should be done using this method for quantitative and qualitative MFA and the Egle et al. (2014a) Austrian P budget as an example. Another study of P-cycles, flows and budgets for all 27 of the European Union Member States was done by van Dijk et al. (2016). However, the data derived were from 2005 and were significantly simplified for better comparability.

2.6 The importance of identifying P-flows

Due to Germany’s lack of phosphate deposits, it is completely dependent on imports of this finite resource. In the past ten years, technological progress has been made to recover phosphorus from waste streams in Germany but a sustainable cycle management of this important raw material has not yet been realized. To measure the existing system, important flows between different processes have to be identified to draw up the existing circumstances for a first step to search for optimizing potential as a next step.

In general, there are three kinds of P-flows:

First, flows that are easy to measure and calculate because data about P-content materials is available and provided by referenced sources.

Second, flows for which data is not easily available by official sources but values are used in former descriptions of the system from other authors. This data should be used with caution because the values of flows can change over time.

Third, flows that are known to exist but no high-quality data is available, only estimations or approximations were possible. These flows should motivate further empiric investigations in the field to receive better data that could show hidden P-losses and P-sinks.

The more detailed P-flows can be measured, the better models and P-budgets can identify optimization potential. If it is possible to calculate a system and follow the flows over time periods of years changes and development in systems can be observed (as in Zoboli et al., 2016). This could lead to taking further optimizations steps.

2.7 Optimization of P-use

The most obvious idea to optimize P-use is to imitate natural P-cycles with the commercial material flows. While the internal agricultural circuit of animal feed production and manure fertilization follows almost a closed loop, the main output from both parts of the agricultural sector that flows into the refining industry and as food to the households break that cycle.

In consuming food, pharmaceuticals, or other P containing products, households produce waste and waste water which still contains considerable amounts of phosphorus. This waste is separated, collected and treated whenever possible. However, phosphorus might not be recovered to the amount that would be feasible. Instead, these flows are passed into sinks, such as landfill sites, or are lost to the hydrosphere. However, it is lost for processes that need phosphorus. On the basis of the findings on phosphorus-containing waste and waste water sectors, these are both to be focused for P-recycling methods.

Even though several P-recycling methods are known, notable amounts of phosphorus are not recovered yet in Germany (BUNB, 2017). Egle et al. (2016) see various stages in waste water treatment plants for phosphorus recovery. Table 1 shows the overview of various techniques presented by Gethke-Albinus (2012), some of which are in the implementation phase with pilot plants and others that are already available on large scale.

Table 1: Comparison of state of the art technology in P-recovery by Gethke-Albinus (2012)

technique	input	Integratability of technology	required connection size	chemical demand	energy require ments	technical status in 2012	output product	Availab ility for plants	by-products	residual waste	P-recovery potential	reference
Crystal-actor	municipal -, industrial waste water	good, in advantage of biological P-elimination in treatment plant	50 m³/h	sand, $Ca(OH)_2$-suspension, $MgCl_2$-solution	low	large-scale	$Ca_3(PO4)_2/NH_4$ $MgPO_4$	yes	none	no	90% of reactor intake	Gethke-Albinus (2012), Giesen (2009)
P-RoC	municipal -, industrial waste water	good	not specified	Tobermorite rich calcium silicate hydrate	low	pilot plant	$Ca_3(PO4)_2$	yes	none	no	90% of reactor intake	Berg (2005)
PRISA	sludge water	good, if biological P-elimination is installed in treatment plant	20 000 E	NaOH-solution, $MgCl_2$-solution	low	technique	MAP	yes	none	no	90 % of reactor intake, 30 % of treatment plant intake	Montag (2008)
Phosnix	sludge water	good	100 m³/d	NaOH-solution, $MgCl_2$-solution, $Mg(OH)_2$	low	large-scale	MAP	yes	none	no	90 % of reactor intake, 50 % of treatment plant intake	Gethke-Albinus (2012)
Pearl	sludge water	good	treatment plant 6.9 mio m³/a (95 000 E), sludge water: 70kg PO_4-P/d, 20 mg PO_4-P/l	NaOH-solution, $MgCl^2$-solution	13 kW/d, 13kW/Mg	large-scale	MAP	yes	none	no	75-95 % of reactor intake, 20-30 % of treatment plant intake	Ostara (2017)
Nishihara	sludge water	good	not specified	Seawater	low	pilot plant	MAP	yes	none	no	70 % of reactor intake, 45 % of treatment plant intake	Gethke-Albinus (2012)
EAWAG-process	urine	not good	not specified	-	high	pilot plant	NPK-solution	yes	none	residual urine	100 % of treatment plant intake	Boller (2007), Gethke-Albinus (20012)
HUBER SE procedure	urine	good	not specified	Mg O	middle	large-scale	MAP	yes	$(NH_4)_2SO_4$ – solution (for fertilizer)	residual urine	80 % of treatment plant intake	Bischof & Paris (2007), Sreeramachandran in Gethke-Albinus (2012)
Biorek	agricultural slurry	not good	7000 m³/a	-	high	large-scale	PK-fertilizer	yes	NH_3 – solution (for fertilizer)	solides	15 to 40 % of treatment plant intake	Gethke-Albinus (2012)
A3-procedure	agricultural slurry	not good	not specified	MgO	high	large-scale	MAP	yes	none	compost fraction	not specified	Brüß (2003)
Schulze-Rettmer	agricultural slurry	not good	not specified	Mg O	middle	technique	MAP	yes	NH_3 – solution (for fertilizer)	compost fraction, „MBR"-surplus sludge	not specified	Schulze-Rettmer (1991) Gethke-Albinus (2012)
NuReBas	urine	not good	not specified	Mg O	middle	technique	MAP	yes	$(NH_4)_2SO_4$ - solution (for fertilizer)	residual urine	90 to 99 % of treatment plant intake	Gethke et al. (2007), Herbst et al. (2006)
Electro-lysis	municipal -, industrial waste water, sludge water, urine	not good	not specified	Mg - / Al - electrodes	high	technique	$Mg_3(PO_4)_2$ / $Al_3(PO_4)_2$	no	hydrogen	no	80 to 95 % of reactor intake	Gethke-Albinus (2012)

3. Methodology

3.1 Material Flow Analysis (MFA)

The methodology of substance flow analysis is used to identify and quantify all relevant phosphorus flows in Germany. Using this MFA, input and output flows, storage and inventory changes for a defined spatial area are recorded in a defined period. The methodology is based on the physical principle of mass conservation:

$$Input = output \ \pm changes\ in\ stock$$

The ÖNORM S 2096-1/2 (2005) is the basis for methodology and its application. The modeling and calculation of the German phosphorus system is performed using the freeware STAN (subSTance flow ANalysis, STAN; Cencic and Rechberger, 2008) which performs the material flow analysis according to ÖNORM S 2096 (2005).

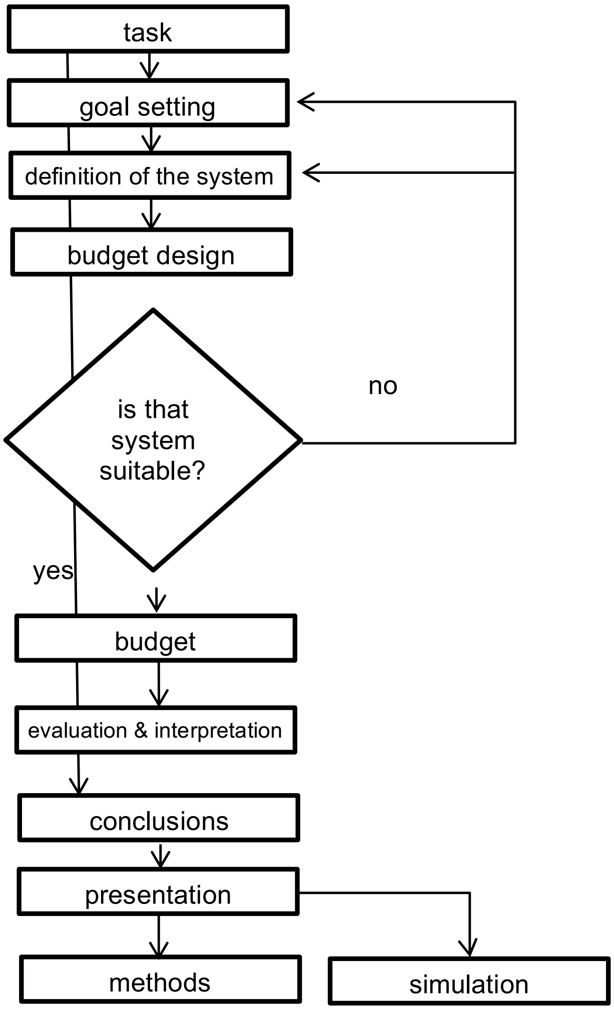

Figure 4: Schematic model for establishing a material flow analysis according to ÖNORM S 2096-2 (2005)

This program allows the input of uncertainties, the calculation of missing values, the consideration of an error propagation and the execution of data reconciliation.

3.2 Uncertainty: uncertainty intervals, uncertainty levels, uncertainty factors

According to Egle et al. (2014a) two parameters are necessary to calculate phosphorus flows; one is the flow size of materials, goods and substances, and the other is its associated phosphorus concentration. Both parameters have different uncertainties. As a result, uncertainty is defined for each material flow and for each concentration. Furthermore, the method of uncertainty calculation by Hedbrant and Sörme (2001) is applied.

Uncertainties are described by uncertainty intervals (UI) that are assumed to include the real value with a probability of 95%.

Any P flow is represented as X ± Y and is assumed to be within the symmetrical interval. This is useful for small uncertainties (e.g., 100 ± 10). However, as uncertainties increase the usefulness of this representation decreases (e.g., 100 ± 200 would result in an interval of [-100; 300]). Therefore, uncertainty factors (UF) are used in such a case.

The uncertainty levels (UL) assigned to material flow and P-concentration depend on the information source. In this P-budget study, the information sources are categorized from 0 to 3 (Table 2), as in Egle et al. (2014a).

Table 2: Uncertainty level for the evaluation of data from different sources according to Egle et al. (2014a)

Uncertainty Level [UL]	**source of information**	**examples**
0	general values (literature)	molecular weight, e.g. P-conversion factor P_2O_5 -> P
1	current and official statistics at local, regional and national level, relevant technical literature	data from the Federal Statistical Office
2 (blue)	older statistics, unofficial statistics, general values for P-contents (literature or on request)	input in biogas plants (calculations necessary), P-content of organic waste
3 (gray)	presentations or publications without literature source	mineral fertilizer application in gardens; own estimations of transfer coefficients

The calculation of the uncertainty factor (UF) is based on the following equations:

$$UF = 1 + 0.036 * e^{1.105*UL} \quad \text{(Eq. 1)}$$

$$UL = \frac{\ln\left(\frac{UF-1}{0.036}\right)}{1.105} \quad \text{(Eq. 2)}$$

As Egle et al. (2014a) explain, the uncertainty factor for a selected uncertainty level of 1 is 1.1. This corresponds to 1 * / 1.1 in the interval [0.909; 1.100] approaching the symmetrical 1 ± 0.1. If on the other hand an uncertainty level of 3 is assumed for the value 1, the calculated uncertainty factor is 2, giving the interval is [1.5; 2.66] and symmetry at 2.08 ± 0.58. Table 3 shows the uncertainty factors as a function of the respective uncertainty level.

Table 3: Uncertainty level, factors, and interval size of data according to Egle et al. (2014a)

uncertainty level UL	**uncertainty Factor UF**	**Interval [UL/UF ; UL*UF]**	**value and symmetric variance**
1	1,1	[0.91; 1.1]	1 ± 0.1
2	1,33	[1.5; 2.66]	2.08 ± 0.58
3	2	[1.5; 6]	3.75 ± 2.25

As mentioned by Egle et al. (2014a), phosphorus concentrations for goods are often given as intervals [A1; A2] for which the geometrical mean value (*m*) has to be calculated using (Eq. 3). Subsequently, the uncertainty level for the probable value is defined by (Eq. 4). The uncertainty factor is calculated by (Eq. 1) as described above.

$$m = \sqrt{A1 * A2} \quad \text{(Eq. 3)}$$

$$UL = \frac{ln\left[\frac{\sqrt{\frac{A2}{A1}} - 1}{0.036}\right]}{1.105} \quad \text{(Eq. 4)}$$

As mentioned above and described by Egle et al. (2014a), the P-load of a flow is calculated by multiplying the quantity of materials and its phosphorus concentration. Each of these two factors is characterized by the corresponding uncertainty factor (UF_1 for the flow value and UF_2 for the concentration value). Using (Eq. 5), a common uncertainty factor ($UF_{1,2}$) is determined for the desired P-flow.

$$UF_{1,2} = 1 + \sqrt{(UF_1 - 1)^2 + (UF_2 - 1)^2} \quad \text{(Eq. 5)}$$

In case flows consist of sub-flows, the $UF_{1,2}$ of each sub-flow has to be calculated and according to (Eq. 6) multiplied with the respective mean (m) in an intermediate step (IS) to get the uncertainty factor of the flow of interest as described by (Eq. 7).

$$IS = (m) * (UF_{1,2} - 1)^2 \quad \text{(Eq. 6)}$$

$$UF_{flow} = 1 + \frac{\sqrt{\sum IS}}{\sum P\ in\ t} \quad \text{(Eq. 7)}$$

In case the input does not correspond to the output and violates the principle of mass conservation, STAN performs data reconciliation to balance the process using the method of least squares.

This means that flows are adjusted to minimize the sum of the squares of all the individual deviations between the measurement and model data. Necessary for this method is an over-determined system of equations (there must be more equations than unknown variables) and uncertainties (Egle et al., 2014a).

4. The German P-budget

4.1 Substance specification, system limits and definition

Substance specification

For this mass flow analysis, masses are given for phosphorus as elementary phosphorus (P). For fertilizers and plant or animal foodstuffs the declaration of the phosphorus content in phosphorus pentoxide (P_2O_5) is common (Blume et al., 2010). Thus, the elementary P load has to be calculated using a factor of 0.437. This factor is calculated using the share of P in the molecular mass of P_2O_5. The calculation tables with P-contents of different materials are located at the end of the annex.

The functional unit used in this analysis is “tons of phosphorus per year” or, in short, “t P/yr”.

System limits and definition

The system is defined by the legal borders of Germany excluding the hydrosphere for simplification. The time span analyzed focuses on the most current data, namely data for 2015. To avoid annual fluctuations, the calculated mean for the years 2014-2016 was used whenever available. The German population in this time period grew from about 80.82 million inhabitants in 2014 to 82.31 million inhabitants in the first half of 2016 according to DESTATIS (2017a) which gives an average of about 81.60 million people. This number is used as the German population when calculating per capita flows and stocks.

4.2 Sectors in Germany using P-containing goods

The basis for the establishment of a German phosphorus budget is the definition of a system, which contains known and relevant phosphorus flows as well as the relevant processes and stocks. The choice of processes for the model is based on the Austrian P-budget (Egle et al., 2014a) for a better comparison and adapted to country specific circumstances.

The different industry sectors of the economy can be described as processes (P) between which phosphorus containing goods/materials flow. Processes can also store phosphorus which leads to an increase in stock. However, processes are treated as a black box and not analyzed in detail. The relevant flows (F) and processes (P) are identified in the qualitative MFA (Figure 5).

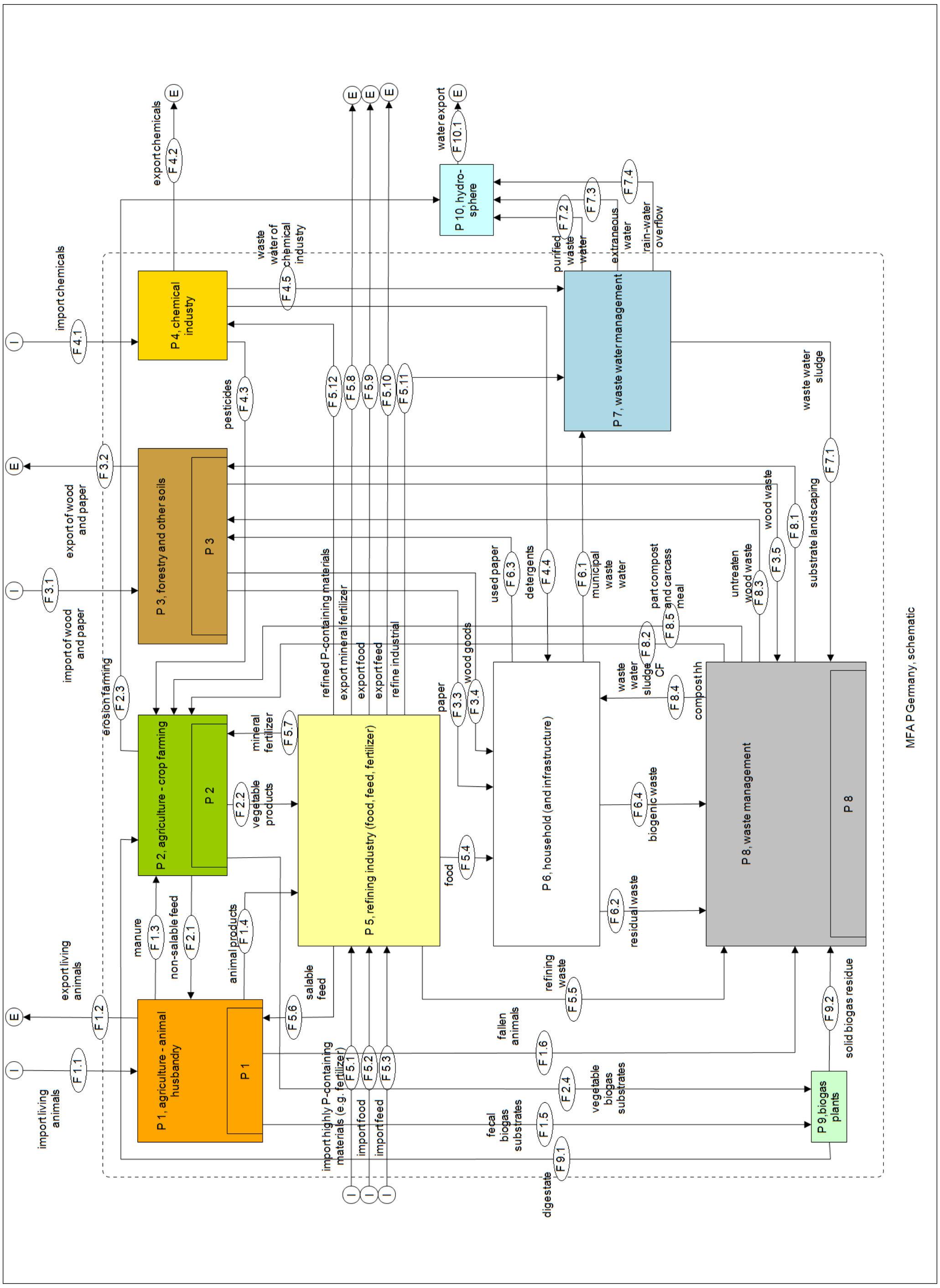

Figure 5: Qualitative Material Flow Analysis for Germany, in accordance with ÖNORM S 2096 for MFA using the freeware STAN

The system consists of the following processes:

(P 1) Agriculture - Animal husbandry
(P 2) Agriculture - Crop farming
(P 3) Forestry and other soils (incl. landscaping)
(P 4) Chemical industry
(P 5) Refining industry (food, feed and fertilizer production)
(P 6) Household (and infrastructure)
(P 7) Waste water management
(P 8) Waste management
(P 9) Biogas plants

Several processes are assigned with a stock but just for three of them, the estimation of the existing P stock is possible (animal husbandry, crop farming, and forestry). The processes exchange goods and materials containing different concentrations of P. The flows calculated in the system are the result of the multiplication of the mass flows of goods and their P concentration. The flows are numbered according to their source process and are listed in Table 4. The explanation of each flow is discussed within the respective source process. Import flows are the only exception. Since they don't have a source process within the system, they are numbered and described in the section pertaining to their destination process.

Agriculture - (P 1) Animal husbandry - (P 2) Crop farming

As in Egle et al. (2014a), agriculture can be essentially subdivided into two processes. First, crop production (P2) for the production of field crops, fruit, vegetables and feed with the stock being soil used in agriculture. Second, animal husbandry (P1) for the production of various animal products such as meat, milk or eggs. The respective stock is all livestock. Between these two processes, there is an intensive exchange of P-containing material flows due to the circulation of phosphorus in the form of feed and manure. The phosphorus input to these processes is through mineral fertilizers, various organic fertilizers (e.g., manure, compost, biogas sludge, waste water sludge), living animals and feed, whereas phosphorus outflow of livestock happens by slaughtering, export of living animals and by harvesting, storm-water overflow and erosion for crop farming, respectively.

(P 3) Forestry and other soils

Similar to Egle et al. (2014a), the process forestry also includes other soils and the downstream processes for the production of timber, lumber and the production of paper. Wood and paper products in Germany result both from its own production as well as from imports. Paper is also recycled in considerable amounts. The forest, wildlife and the forest soil are taken into account as P-stock. Furthermore, waste that ends up in landscaping is considered here under “other soils”.

(P 4) Chemical industry

The chemical industry imports phosphorus containing chemicals for the production of detergents, insecticides and other chemicals or already the finished products. Pesticides for agriculture are partly imported, but are also produced for in-country consumption and exported. However, data availability on the specific type of pesticide is very limited. Furthermore, pharmaceuticals and drugs fall in this category.

(P 5) Refining industry (including food, feed and fertilizer production)

The refining industry is the process in which animal and vegetable raw materials from agriculture and forestry are processed and converted to food and animal feeds, subsequently sold or exported as products to household (P 6) or back to crop farming (P 2), or animal husbandry (P 1). In addition to the processing of products, the refining industry serves as a distributor for imported food, feed, phosphate and fertilizer for households and the agricultural sector and exports of refined goods.

(P 6) Household (and infrastructure)

The process household includes consumption goods for private households as well as for public infrastructure such as schools or for goods used in office buildings etc. (e.g. furniture, food and detergents). Most inflows are transformed (e.g. digested) and leave the process as residual waste, separately collected biogenic waste are introduced into the process of waste management. Used paper flows directly back to the paper industry (P 3 forestry).

The human feces, detergents and fractions of precipitation water enter the waste-water treatment process (P 7) via the municipal waste-water and are treated there.

(P 7) Waste water management

Municipal waste water as well as industrial waste water is treated in waste water treatment plants. A small part, almost negligible in Germany, of the waste water flows directly into the water body of the hydrosphere, while the largest share of waste water flows into the treatment system. Waste water sludge is further processed, recycled or deposited in the waste management process. Phosphorus, which is not removed with the waste water sludge, enters the hydrosphere as purified waste water.

(P 8) Waste management

The different waste fractions of the processes animal husbandry (P 1), crop farming (P 2), chemical (P 4) and refining industry (P 5), households (P 6) and waste water (P 7) are collected, treated and recycled or deposited. Treatment and utilization possibilities for the various waste fractions are mechanical-biological waste treatment plants, composting plants, animal body treatment plants and thermal plants. The thermal treatment distinguishes between refuse, mono- and co-incineration plants. Biogenic conversion products, such as composts are used in agriculture or garden areas in private households. Minerals from animal waste, like meat and bone meal, are used in crop farming (P 2) after thermal treatment due to the feed inhibition since the scandals related to bovine spongiform encephalopathy (BSE). The rest is either used in landscaping (F 8.1) or landfilled.

(P 9) Biogas plants

Biogas plants are important in Germany, for example as bio-fuel producers. Biogas slurry is mainly used in crop farming and a solid residue in the compost fraction.

(P 10) Hydrosphere

Phosphorous inputs into the waters are carried out on the one hand via diffuse entries, e.g. erosion mainly from farming soils and further leaching from soil into groundwater, or by point sources, such as purified waste water from treatment plants. The hydrosphere serves more as a final sink than as a process in the anthropogenic P-budget. However, this model excludes the hydrosphere from the system for feasibility reasons. It is displayed only to provide the reader with a better understanding of flows and their final sinks.

Table 4: Table of flow names and directions

Flow	Flow name	Source process	Destination process
F 1.1	import living animals	import	P 1, animal husbandry
F 1.2	export living animals	P 1, animal husbandry	export
F 1.3	manure	P 1, animal husbandry	P 2, crop farming
F 1.4	animal products	P 1, animal husbandry	P 5, refining industry
F 1.5	fecal biogas substrates	P 1, animal husbandry	P 9, biogas plants
F 1.6	fallen animals	P 1, animal husbandry	P 8, waste management
F 2.1	non-salable feed	P 2, crop farming	P 1, animal husbandry
F 2.2	vegetable products	P 2, crop farming	P 5, refining industry
F 2.3	erosion farming	P 2, crop farming	P 10, hydro-sphere
F 2.4	vegetable biogas substrates	P 2, crop farming	P 9, biogas plants
F 3.1	import of wood and paper	import	P 3, forestry
F 3.2	export of wood and paper	P 3, forestry	export
F 3.3	paper	P 3, forestry	P 6, household
F 3.4	wood goods	P 3, forestry	P 6, household
F 3.5	wood waste	P 3, forestry	P 8, waste management
F 4.1	import chemicals	import	P 4, chemical industry
F 4.2	export chemicals	P 4, chemical industry	export
F 4.3	pesticides	P 4, chemical industry	P 2, crop farming
F 4.4	detergents	P 4, chemical industry	P 6, household
F 4.5	waste water of chemical industry	P 4, chemical industry	P 7, waste water management
F 5.1	import highly P-containing materials (e.g. fertilizer)	import	P 5, refining industry
F 5.2	import food	import	P 5, refining industry
F 5.3	import feed	import	P 5, refining industry
F 5.4	food	P 5, refining industry	P 6, household
F 5.5	refining waste	P 5, refining industry	P 8, waste management
F 5.6	salable feed	P 5, refining industry	P 1, animal husbandry
F 5.7	mineral fertilizer (agriculture)	P 5, refining industry	P 2, crop farming
F 5.8	export mineral fertilizer	P 5, refining industry	export
F 5.9	export food	P 5, refining industry	export
F 5.10	export feed	P 5, refining industry	export

F 5.11	refine industrial waste water	P 5, refining industry	P 7, waste water management
F 5.12	refined P-containing materials	P 5, refining industry	P 4, chemical industry
F 6.1	municipal waste water	P 6, household	P 7, waste water management
F 6.2	residual waste	P 6, household	P 8, waste management
F 6.3	used paper	P 6, household	P 3, forestry
F 6.4	biogenic waste	P 6, household	P 8, waste management
F 7.1	waste water sludge	P 7, waste water management	P 8, waste management
F 7.2	purified waste water	P 7, waste water management	P 10, hydrosphere
F 7.3	extraneous water	P 7, waste water management	P 10, hydrosphere
F 7.4	rain-water overflow	P 7, waste water management	P 10, hydrosphere
F 8.1	substrate landscaping	P 8, waste management	P 3, forestry
F 8.2	waste water sludge CF	P 8, waste management	P 2, crop farming
F 8.3	untreated wood waste	P 8, waste management	P 3, forestry
F 8.4	compost hh	P 8, waste management	P 6, household
F 8.5	part compost and carcass meal cf	P 8, waste management	P 2, crop farming
F 9.1	digestate	P 9, biogas plants	P 2, crop farming
F 9.2	solid biogas residue	P 9, biogas plants	P 8, waste management
F 10.1	water export	P 10, hydrosphere	export

5. Data

Following Egle et al. (2014a), all flows are connected to a source process and a destination process. The following list provides information on the flow composition and calculation as well as data sources for flows and the according P concentration. All these flow data, together with their uncertainty factors, were calculated in an extra file (see Table 9, Annex) and inserted into the schematic model of the German P-budget (Figure 5).

Phosphorus concentrations of the individual agricultural products are derived from the Kroiss et al. (1998) and Zessner and Lampert (2002) nutrient table and are used for all flows in agriculture and foodstuffs (Table 6). Information on animal manure (Table 5) is provided by the Austrian Ministry for Agriculture, Forestry, Environment and Water Management (BMLFUW, 2006) and data on organic waste (Table 7) by Egle et al. (2014a).

Flows are ordered by flow number.

F 1.1 Import of living animals (from import to animal husbandry) and F 1.2 Export of living animals (from animal husbandry to export)

The P-load of imported and exported livestock, such as cattle, pig, sheep, poultry and horses was calculated using P concentrations from Table 6 and import/export information provided by DESTATIS (2017b) for the years 2014 to 2016. Fish is part of food imports (F 5.2).

F 1.3 Manure (from animal husbandry to crop farming)

This flow, together with the mineral fertilizers (F 5.7), provides phosphorus supply for agricultural soils. The calculation of the P-load of manure is based on data for 2015 by the German Statistical Office (DESTATIS, 2017c). Solids and liquid manure as well as poultry dropping were distinguished and P-content calculated according to Kratz et al. (2014). 1 m³ of slurry was equalized to 1 t.

F 1.4 Animal products (from animal husbandry to refining industry)

This flow is consists of both slaughtered animals (cattle, calves, pigs, horses, sheep, goats, poultry and fish from fish-farms) as well as animal products such as milk and eggs together and flows for further processing steps in the refining industry (P 5). For the calculation of the P concentrations, Table 6 was used. Most data (2014 to 2016) for flow calculations was from DESTATIS (2017d), except for data on milk which was provided by the Dairy Industry Association of Germany (2016) for the years 2015 and 2016. The quantities of milk, which remain in the farm as feed, is not included in that flow.

F 1.5 Fecal biogas substrates (from animal husbandry to biogas plants)

Bovine and porcine manure and dung are used as substrates for biogas plants. Unfortunately, data is only available for the year 2014 (DESTATIS, 2016). P concentration were taken from the tables mentioned above.

F 1.6 Fallen animals (from animal husbandry to waste management)

Animals that died during the keeping, transport or for other reasons (victims of diseases) are called fallen animals. These are not allowed to be consumed and arrive directly in (P 8) waste management for treatment. Data for 2016 was available by STN (2017) assuming a share of 15.5% bones and 84.5% meat per animal as in Egle et al. (2014a).

F 2.1 Non-salable feed (from crop farming to animal husbandry)

This flow of feed captures basically field fodder from grassland and pastures. Data from Frede (as cited in Gethke-Albinus, 2012) was used.

F 2.2 Vegetable products (from crop farming to refining industry)

This flow contains harvest data from all vegetables, fruits, grains and wine available from 2015 and 2016 from DESTATIS (2017e, 2017f, 2017g, 2017h) also compared with the data from the German Farmers' Association (2017a), calculated with the P-concentration of Table 6.

F 2.3 Erosion (from crop farming to hydrosphere)

Rainfall on agricultural areas causes erosion of soil and nutrients, which cannot be measured easily. Therefore, the estimate of Behrendt et al. (as cited in Gethke-Albinus, 2012) was used. Even though this data might be outdated, it provides a good idea of the size of this flow.

F 2.4 Vegetable biogas substrates (from crop farming to biogas plants)

Input material for biogas plants from farming are silages from corn, grass and rye, as well as other grasses. Data is only available for the year 2014 (DESTATIS, 2016) and P concentration is taken from Table 7.

F 3.1 Import wood and paper (from import to forestry) and F 3.2 Export wood and paper (from forestry to export)

Data on imported and exported wood was taken from Weimar (2016) whereas data on import and export of paper was provided by the Federal Environmental Agency (2017). Both set of information was only available for 2014 and 2015. The P concentration in Table 7 was used.

F 3.3 Paper (from forestry to household)

The paper P-flow comes from paper data from combined with the P-content of used paper from Table 7. The annual paper consumption is about 20.5 million tons for Germany (Federal Environment Agency, 2017). Due to the very low phosphorus concentration (0.005 to 0.007% in Table 7) in the paper, this flow plays only a subordinate role in the phosphorus budget. Unfortunately, there is no information available for paper used in private households and infrastructure (P 6) or in industry. However, since (P 6) households also includes office buildings, the flow is only directed to (P 6) and no additional distinction has been made.

F 3.4 Wood goods (from forestry to household)

Since it was not possible to get data for timber, lumber and fire wood separately, all flows were calculated as “wood goods”. Wooden goods are those goods which enter the households either directly as a wood for firing; also industrial wood, bark, chopped wood, and woodchuck, and also furniture mainly from domestic forestry. Leaves, branches and roots are not included. Information on quantity was taken from the current analysis by Weimar (2016) who finds a demand of 115 million (2014) to 119 million (2015) m³ of wood per year in Germany. This was calculated to 1.87 t per m³ as an average of different wood species after Riegger (2008), then combined with the P-values for old woods due to Table 9. This calculation method is the same for all flows in the forestry process.

F 3.5 Wood waste (from forestry to waste management)

The wood waste flow comes from the data from DESTATIS (2016) combined with the P-content of old wood from Table 7.

F 4.1 and 4.2 Import and export of chemicals of the chemical industry

In this flows, phosphorus-containing chemicals and pesticides are considered. This includes other detergents and herbicides as well as insecticides. The collection of data for these flows turned out to be very difficult because of the inconsistent declaration in the foreign trade results as well as the non-publication of ingredients of this product group. Therefore, the values used by Gethke-Albinus (2012) were used for both flows: Information on import chemicals for detergents was provided by the Federal Statistical Office of Germany (Statistisches Bundesamt, 2010) and CEEP (2009), on import chemicals for household by the Federal Statistical Office of Germany (Statistisches Bundesamt, 2010) and IKW (2006), on phosphorus containing materials for industry by the Federal Statistical Office of Germany (Statistisches Bundesamt, 2010); information on exports of detergents was provided by the Federal Statistical Office of Germany (Statistisches Bundesamt, 2010), and on exports of chemicals used in the phosphorus industry by the Federal Statistical Office of Germany (Statistisches Bundesamt, 2010) and IKW (2006a) (all as cited in Gethke-Albinus, 2012).

F 4.3 Pesticides (from chemical industry to crop farming)

The German Farmers' Association (2017b) proclaims a use of 48,600 t of pesticides for 2015, mainly herbicides, in the last years. Unfortunately, there was no data available on the type of pesticide to calculate the phosphorus for the specific pesticides. Therefore, the value for Austria used in Egle et al. (2014a) was taken and multiplied by 10. This proxy approach is reflected in the high uncertainty of this value.

F 4.4 Detergents (from chemical industry to household)

The value by Gethke-Albinus (2012) was used due to lack of detailed data on the type of detergent which would be necessary to calculate the P load.

F 4.5 Waste water of chemical industry (from chemical industry to waste water management)

Due to a lack of information on P concentration in waste water stemming from the chemical industry, the Austrian value in Egle et al. (2014a) was used and adapted. Using the same share of industrial waste water of total waste water as in Austria, provides a proxy for the chemical industry's waste water in Germany. This approach seems reasonable since the regulations for pre-treatment are similar.

F 5.1 Import of highly P-containing materials (e.g. fertilizer) to refining industry

The value used by Gethke-Albinus (2012) was chosen which is composed of P loads on imported rock phosphate and imported phosphorus containing materials provided by the Federal Statistical Office of Germany (Statistisches Bundesamt, 2010, as cited in Gethke-Albinus, 2012), and import of mineral fertilizer by the Agricultural Industry Association (Industrieverband Agrar e.V., 2009, as cited in Gethke-Albinus, 2012).

F 5.2 Import food to refining industry

Data on imported food was taken from DESTATIS (2017i) for the year 2013 and the five most important trading partners. This flow also includes imported fish (processed and fresh) with an estimated amount of 800,000 t provided by Statista (2017).

F 5.3 Import feed to refining industry

Imported feed consists of the soy import and oilcake and other solid soy residues. Data source was the German Farmers' Association (2017a).

F 5.4 Food (from refining industry to household)

To estimate the amount of P-content in food for the population, the value of Gethke-Albinus (2012) was used.

F 5.5 Waste (from refining industry to waste management)

This flow consists of waste from slaughtering and the share of non-meat waste in the refining industry. Data was used from STN (2017) and DESTATIS (2016) and concentrations are from Table 6 and Table 7. This flow is very rich in phosphorus due to the bone content and other abattoir waste.

F 5.6 Salable feed (from refining industry to animal husbandry)

The feed includes feed from arable farming (e.g. wheat, legumes etc.), feedstuffs from industry by-products (milling, brewing, distilling, starch and sugar and oil) protein-containing fodder plants from abroad (soy). Data was taken from Frede (as cited in Gethke-Albinus, 2012) due to lack of more adequate data.

F 5.7 Mineral fertilizer agriculture (from refining industry to crop farming)

Unfortunately, old data for 2013 in Kratz et al. (2014) had to be used.

F 5.8 Export mineral fertilizer

Data of the Agricultural Industry Association (2009) (as cited in Gethke-Albinus, 2012) was used.

F 5.9 Export food and F 5.10 Export feed

For the amount of P-content in food and feed for export, the value used in Gethke-Albinus (2012) was chosen.

F 5.11 Refine industrial waste water (from refining industry to waste water management)

Determining the origin of waste water in Germany was not possible since all German waste water meets in the treatment plants. Therefore, data on waste water from the fertilizer industry by the Federal Statistical Office of Germany (Statistisches Bundesamt, 2006, as cited in Gethke-Albinus, 2012) and ATV-DVWK (2003) (as cited in Gethke-Albinus, 2012) and other industrial waste water as in Gethke-Albinus (2012) was used.

F 5.12 Refined P-containing material (from refining industry to chemical industry)

This flow of various P containing materials in different forms and compounds (e.g. pure phosphorus, phosphoric acid and polyphosphoric acid, phosphoric acid for industry (10%), phosphorus trichloride oxide, - trichloride, - pentachloride - chloride and - sulphides including phosphorus trisulfide and phosphates) was unfortunately not clearly identifiable. Therefore, the value by the Federal Statistical Office of Germany (Statistisches Bundesamt, 2010, as cited in Gethke-Albinus, 2012) is used.

F 6.1 Municipal waste water (from households to waste water management)

The municipal waste water flow was provided by the Federal Statistical Office of Germany (Statistisches Bundesamt, 2006, as cited in Gethke-Albinus, 2012) and by ATV-DVWK (2003) (as cited in Gethke-Albinus, 2012).

F 6.2 Residual waste (from households to waste management)

Residual waste in Germany is made up from different contents but it is already reduced in plastics, metals, and paper products because these materials are collected separately. The information used was provided by the DESTATIS (2016) as mentioned in the calculations in Table 9.

F 6.3 Used paper (from households to forestry)

Every year, about 15 million tons of used paper is collected and recycled into the paper industry (Federal Environmental Agency, 2017). Data by the Federal Environmental Agency (2017) was used for calculations.

F 6.4 Biogenic Waste (from households to waste management)

Contains waste fractions like kitchen waste, gastronomy sector, garden and park and other waste. Data by DESTATIS (2016) was used.

F 7.1 Waste water sludge

In Germany, 97% of all industrial and municipal waste water flows through the treatment system (DESTATIS, 2017j). Waste water sludge qualities depend on sources and treatment methods. Data were hard to find and are only available for the year 2014 and 2015 (DESTATIS, 2017j) but include all German waste water sludge (municipal and industrial), calculated with the P-contents of sludge from Table 7.

F 7.2 Purified waste water (from waste water management to hydrosphere)

The entire industrial and municipal waste water is purified by treatment plants. However there is no consistent P concentration in purified water. Therefore an estimation by Behrendt et al. (as cited in Gethke-Albinus, 2012) was used.

F 7.3 Extraneous water (from waste water management to hydrosphere)

Extraneous water enters from leakages in the drainage system or running wells or can be illegally discharged water, sometimes it occurs at maintenance or construction sites and flows directly into the hydrosphere. Data is for 2013 and provided by DESTATIS (2017k).

F 7.4 Rain-water overflow (from waste water management to hydrosphere)

Rainwater overflow is difficult to quantify and no data could be found. Therefore, data by Egle et al. (2014a) on Austria was used and increased tenfold thereby just accounting for differences in size but not meteorological patterns.

F 8.1 substrate landscaping (from waste management to forestry)

The substrate for landscaping is available by DESTATIS (2017j) for 2015. Reusing substrate is better than landfilling – given that no toxic or hazardous substances contaminated the substrate.

F 8.2 Waste water sludge CF (from waste management to crop farming)
Data was taken from DESTATIS (2017j) for 2014 and 2015.

F 8.3 untreated wood waste (from waste management to forestry)
The (untreated) wood waste is a value that could be calculated using data from Weimar (2016) with the P-content of wood waste Table 7.

F 8.4 Compost (from waste management to household)
Part of compost goes back to private households for gardening. Data on this part of compost was used from Kratz et al. (2014).

F 8.5 Part compost and bone meal (from waste management to crop farming)
This flow reuses bone or carcass meal as well as part of the compost in the agricultural sector, namely crop farming. Data by Kratz et al. (2014) was used.

F 9.1 Digestate (from biogas plants to crop farming)
The biogas slurry is usually recycled to agricultural areas or used in landscaping (P 3). Despite the mass and volume loss of the substrate, the P-content remains. This value was calculated as the residual to equal the inflows (fecal and vegetable biogas substrate F 1.5 and F 2.4) and the other outflow (solid biogas residue F 9.2).

F 9.2 Solid biogas residue (from biogas plants to waste management)
DESTATIS (2017c) provides data for 2015.

F 10.1 Export waters
This flow is the sum of all above identified inflows into the hydrosphere such as erosion, purified waste water, extraneous water and rainwater overflow.

The flows entering and existing the processes change the stock of the respective process. As mentioned above, three of the identified processes are assigned with a stock:

(S 1) Livestock
This stock considers all livestock of agriculture as stock. Data is provided by DESTATIS (2017l) and P-concentrations are taken from Table 6.

(S 2) Agricultural soil and (S 3) Forests and other soils
The P stock is calculated by multiplying the P concentration with the hectares of soil used in agriculture or forestry, respectively. However, data collection turned out to be very difficult especially due to the lack of representative soil samples' P concentration. As a proxy, the Austrian values by Egle et al. (2014a) were used and multiplied by ten to give

an idea about the stock. However, both values have to be taken cautiously which is visible in the high uncertainty.

Additionally, (P 8) Waste management shows a change in stock but the built-up P- stock is unknown. The change in stock of waste management is basically all products that are landfilled and still contain phosphorus.

6. Results

The flow diagram in Figure 7 gives the results of the data reconciliation of the quantitative Material Flow Analysis for phosphorus in Germany for the year 2015. STAN represents the flows in the form of arrows whose width is proportional to the P-load (Sankey diagram). Furthermore, the size of the P-load and its uncertainty are indicated in the flow-arrows. Also the stock and stock changes are indicated in the process-representations. The flows and stock changes are rounded to two significant digits in t of P/yr with their calculated uncertainty given in percentages. The stocks are given in t of P and also rounded to two significant digits. The colors of the flow-arrows correspond to the uncertainty level of the data source as mentioned in Table 2. The black arrows represent data from the Statistical Office or other official sources, blue arrows are flows including values from other authors, grey arrows show flows that were calculated or approximated using for instance the Austrian P-budget.

Table 8 gives an overview of all flows sorted by process and provides information of calculated loads and their uncertainties before and after data reconciliation. For a more detailed investigation, Table 9 of the Annex provides all calculations of P loads and the respective uncertainties.

Furthermore, as mentioned in Klinglmair et al. (2016, p. 174), “Metadata matter” to evaluate the quality of a study and its contribution. Therefore, Figure 6 provides information on the uncertainty ranges used in this thesis after data reconciliation which gives an idea about the reliability of the results. Only nine flows (or 19%) exhibit uncertainties of 0-20%, most flows (35%) have uncertainties of 21-40%, and ten flows (or 21%) are with uncertainties from 41% to 60%.[3] The highest uncertainty is observed for flows with high masses such as wood products or a wide span of P content such as biogenic waste.

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[3] 0-20% (9 flows): wood waste, import chemicals, export chemicals, waste water of chemical industry, refine industrial waste water, extraneous water, compost to hh, compost and bone meal to cf, digestate;
21-40% (17 flows): non-salable feed, vegetable products, erosion farming, detergents, import of highly P-containing materials, import feed, food, salable feed, mineral fertilizer, export mineral fertilizer, export food, export feed, refined P-containing materials, municipal waste water, waste water sludge, waste water sludge used in cf, water export;
41-60% (10 flows): import living animals, export living animals, animal products, fallen animals, refining waste, residual waste, purified waste water, rain water overflow, untreated wood waste, solid biogas residue
61-80% (6 flows): manure, vegetable biogas substrate, paper, import food, used paper, substrate landscaping;
>80% (6 flows): fecal biogas substrate, import of wood and paper, export of wood and paper, wood goods, pesticides, biogenic waste.

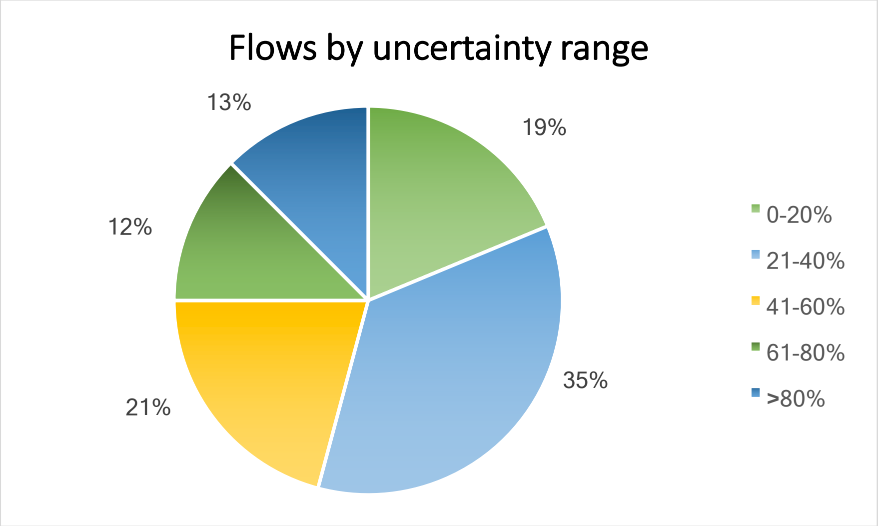

Figure 6: Share of flows sorted by five uncertainty ranges

As we can see in Figure 7, Germany has a total import of P of 360,000 t per year and exports 340,000 t P/yr. The stock increase of about 21,000 t P is unfortunately tainted with a very high uncertainty. The stock values for the processes were calculated in Table 9 but the changes in stock were calculated by STAN. Landfilling (P 8) seems to be the major sink of P with an accumulation of 64,000 t P. Changes in stock of other processes are highly uncertain but there seems to be a decrease in P for both agriculture processes, animal husbandry (P 1) and crop farming (P 2) and an increase for (P 3) forestry and other soils.

Major flows in the German P budget are non-salable feed (F 2.1) with 290,000 t P/yr, manure (F 1.3) with 270,000 t P/yr, import of highly P-containing materials such as fertilizer (F 5.1) with an amount of 200,000 t P/yr and food exports (F 5.9) with 170,000 t P/yr.

The process with the highest P transfers is (P 2) crop farming. Crop farming has also the largest stock of P in the soil (120,000,000 t P) although uncertainties are considerable (140%). However, it is interesting that mineral fertilizer (130,000 t P/yr) seems to play a smaller role than the available alternatives such as especially manure (270,000 t P/yr), compost and bone meal (38,000 t P/yr) and waste water sludge (12,000 t P/yr). Furthermore, we see that crop farming (P 2) and animal husbandry (P 3) form almost a closed cycle in exchanging 270,000 t P/yr of manure (F 1.3) used as fertilizer and 290,000 t P/yr (non-salable) feed (F 2.1).

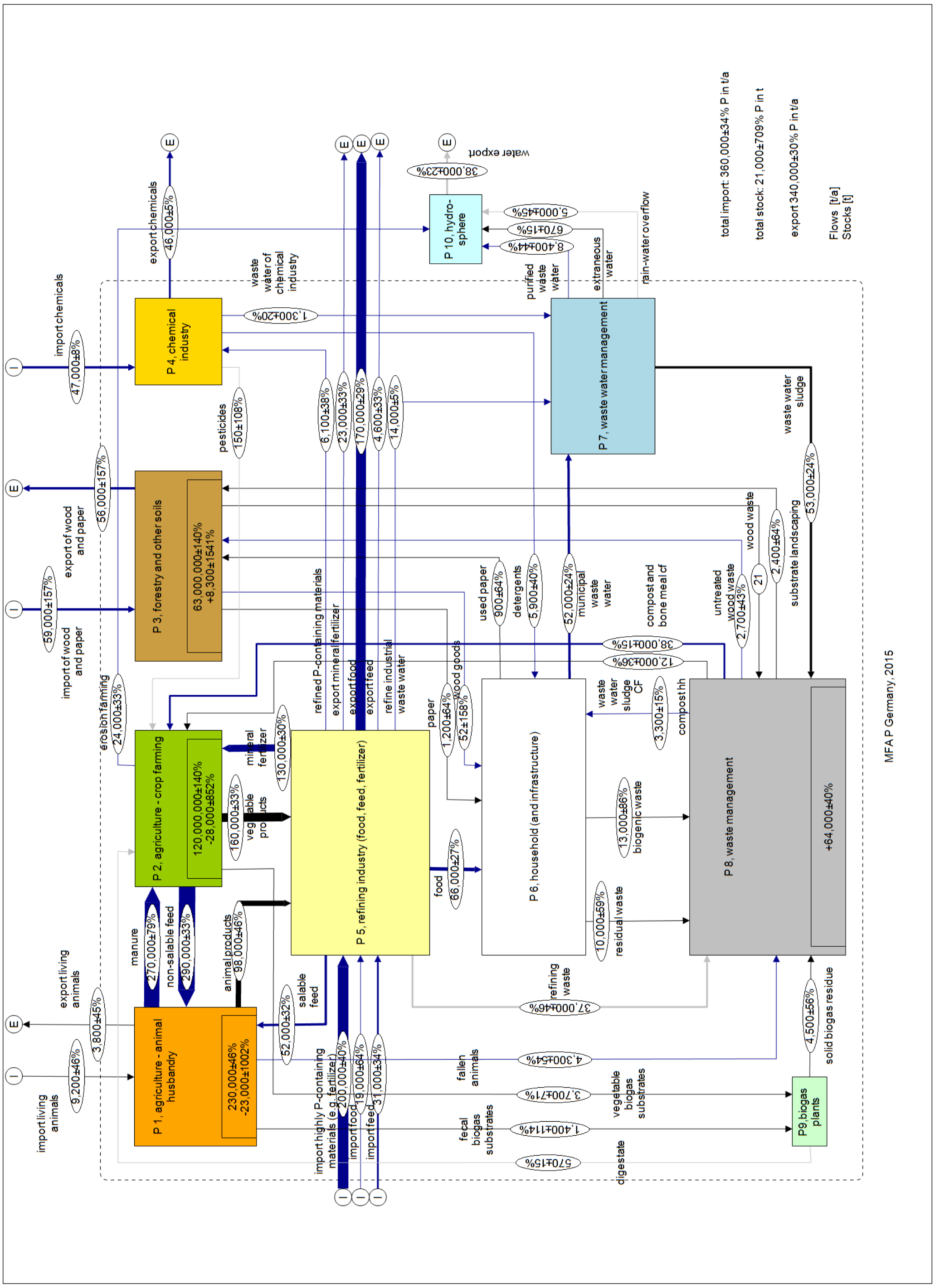

Figure 7: Quantitative Material Flow Analysis for phosphorus in Germany, 2015. Flows are in t P/yr and stocks in t P.

Additionally, flows related to food add almost up which may imply a good description of the system even though uncertainties are up to 64% (for food imports). Vegetable and animal products entering the refining industry account for 160,000 t P/yr and 98,000 t P/yr respectively. Adding imported food with 19,000 t P/yr and subtracting food exports (170,000 t P/yr) and food for household consumption (66,000 t P/yr) gives an unaccounted 41,000 t P/yr which represents only 8% of all P flows related to food.

The share of fallen animals of total animals (4301.6t P/228098.2t P) is with 2% of total livestock lower than in Austria with almost 4%[4].

The chemical industry (P 4) plays a subordinate role in the German P budget. Even though imports are considerable (47,000 t P/yr), most chemical products such as detergents, medication etc. are exported again (46,000 t P/yr) and only a small fraction of 5,900 t P/yr enters the German market (F 4.4).

The same holds true for (P 3) forestry and other soils. Except for the large stock of P in forests and other soils using e.g. landscaping substrate, the main flows of this process are the import (F 3.1) and export (F 3.2) of wood and paper which are of about the same size, 59,000 t P/yr and 56,000 t P/yr respectively, but highly uncertain (157%). All other flows are high in tons but due to the low P concentration in paper and wood (see Table 7) they play a minor role in the system as a whole.

In waste management, the most important flows are the inflow of waste water sludge from waste water treatment (F 8.2) amounting to 53,000 t P/yr and the outflow of waste water sludge to crop farming (F 7.1) 12,000 t P/yr. Using the MFA, we can calculate a reuse of 23% of the treated waste water sludge in crop farming (F 8.2).

In comparison to Gethke-Albinus (2012), biogas plays a much smaller role in this analysis. However, the high uncertainties of biogas substrates might indicate the need for more accurate information.

Figure 8 shows the P loads in kg per capita for the year 2015. This representation simplifies the comparison of the results to other countries or former studies. Comparing the P-budget per capita of Austria (Egle et al. 2014a) and Germany offers interesting insights on differences and similarities.

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[4] Calculation for Austria uses data provided by Egle et al. (2014a): Fallen animals (266 t P/ yr) divided by total stock of animals (6989 t P) gives 3.806%

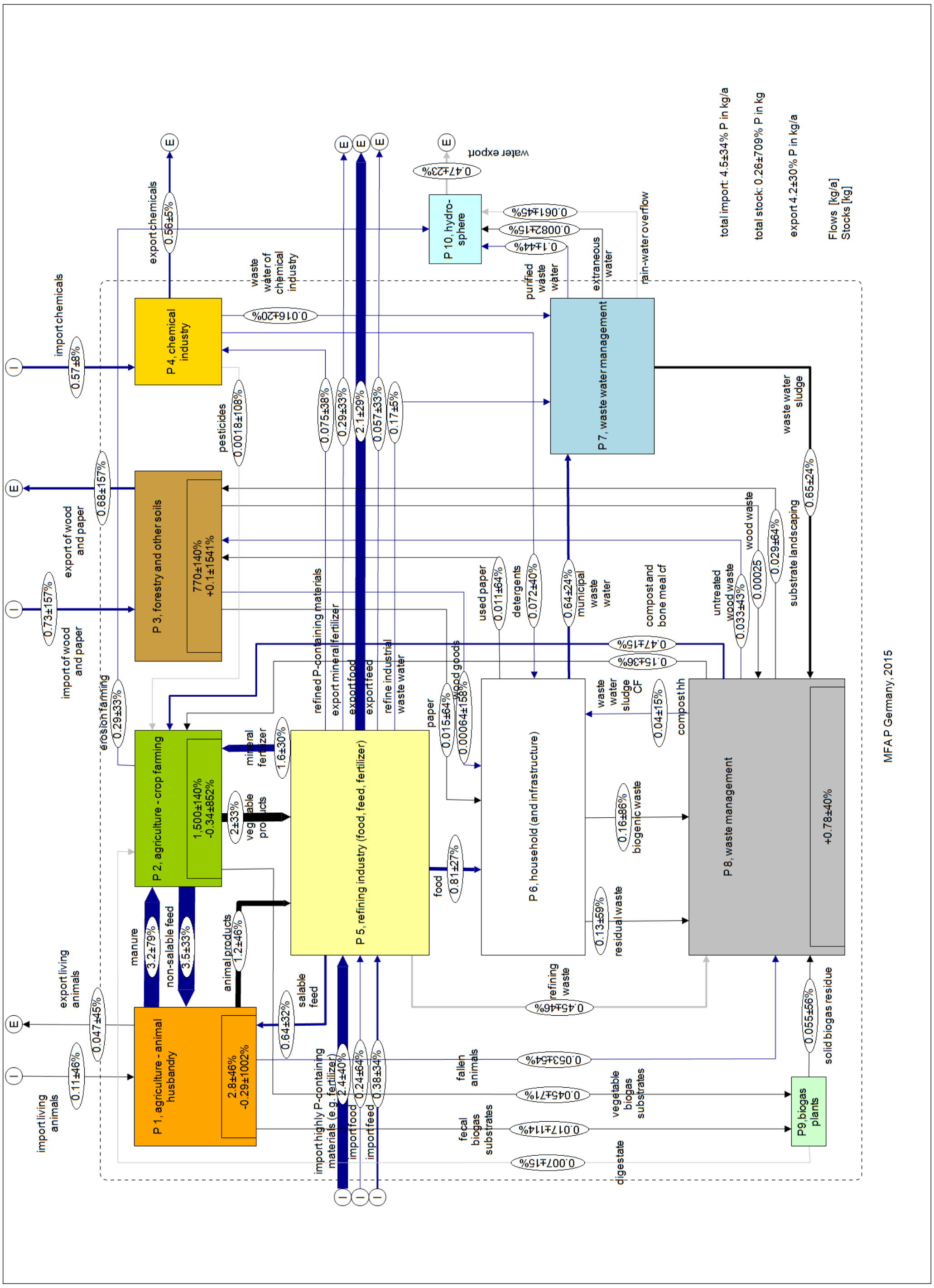

Figure 8: German P budget per capita for 2015 in kg P/(cap*yr)

Firstly, Germany has a higher livestock per capita (2.8 kg P/cap as opposed to 0.84 kg P/cap) and three times higher imports of living animals (0.11 kg P/ (cap*yr) as opposed to 0.045 kg P/ (cap*yr)) which indicates the importance of animal in German agriculture. Furthermore, Germany plays an important role in food processing and export (2.1 kg P/ (cap*yr) as opposed to 0.31 kg P/ (cap*yr) in Austria). Whereas Austria shows high flows for fertilizer import and exports (5.8 kg P/ (cap*yr) in Austria opposed to 2.4 kg P/ (cap*yr) in Germany for imports and 3.9 kg P/ (cap*yr) and 0.29 kg P/ (cap*yr) for exports respectively).

Secondly, households and infrastructure (P 6) seem to be comparable. The amount of food provision in Germany of 0.81 kg P/ (cap*yr) does not seem to be very different from Austria with 1 kg P/ (cap*yr). The same holds true for residual waste with an amount of 0.13 kg P/ (cap*yr) for Germany and 0.14 kg P/ (cap*yr) for Austria as well as municipal waste water with 0.64 kg P/ (cap*yr) for Germany and 0.7 kg P/ (cap*yr) for Austria.

Thirdly, both countries apply treated compost and bone meal (0.47 kg P/ (cap*yr) for Germany and 0.6 kg P/ (cap*yr) for Austria) as well as waste water sludge (0.15 kg P/ (cap*yr) in Germany and 0.12 kg P/ (cap*yr) in Austria) in crop farming to benefit from the P content in addition to manure – the most prevalent for both countries with 3.2 kg P/ (cap*yr) in Germany and 3.3 kg P/ (cap*yr) in Austria – and mineral fertilizers (1.6 kg P/ (cap*yr) in Germany and 2 kg P/ (cap*yr) in Austria).

It seems as if both countries are similar in their household structure and individual consumption patterns but differ in the type of industry that exports most P. Additionally, we might suspect that both countries – given that Austria is an exporter of large amounts of fertilizer and Germany exports food – seem to complement each other. However, further investigations in trade patterns is needed to clarify the exchange of P of these two countries.

7. Conclusion

Germany is well aware of the unused potential of P and several steps were undertaken to tackle this issue in legislation (see chapter 2.4) and pilot projects of P recovery technologies (see Table 1). Still, more could be done. The most feasible way to recover P is treatment in waste management and waste water management; the two destination processes of all collected material from households and industries. Focusing on P recovery methods preventing P landfilling has the highest and most visible potential for the near future. In 2015, 44,449,100 t of waste were landfilled which is a small improvement from 45,010,900 t of waste in 2014 (DESTATIS, 2017m).

Emissions from diffuse sources such as erosion from farming are more difficult to cope with and undertaken measures might not show immediate but time lagged results. However, this does not mean that possible improvements should be ignored but that policy makers have to take decisions wisely, proving foresight and patience. For example, Prasuhn (2005) could show in his study in agriculturally used areas in the canton of Bern in Switzerland that erosion is highest directly after plowing. In this context, soil-conserving cultivation techniques such as permaculture or erosion-inhibiting plowing techniques like plowing parallel to the topographic gradients of the cultivation area and the building of field erosion barriers inhibit potential to reduce P erosion in Germany.

Given the similar consumption patterns of households in Germany and Austria, measures to improve P consumption of households are similar to the ones identified by Zoboli et al. (2016) namely, a) improvement in separate collection and substance specific treatment, b) reduce food waste, c) adapt diet to a less P intense production of food, and d) reduce overuse of fertilizers in private gardens. However, individual’s preferences are difficult to predict and might not lead to major changes in the foreseeable future. Nonetheless, the example of indigenous people of the amazon rain forest who developed a special quality of soil, called “terra preta” (black soil), to prevent soil nutrients from washing out could also be applied in small scale farming or gardening this side of the world. They mixed their kitchen, greenery waste and excreta with charcoal, which had been soaked up with urine as a P source. The charcoal serves like a long-lasting humus compound but also as a nutrient battery. Due to the very high surface of the charcoal, thanks to the porous structure, it is possible for the nutrient salt ions like P to stay at that surface even under extreme conditions such as daily rain. The fertilizing potential of this “terra preta” is still measurable after centuries (Schmidt, 2010). Using this method in gardening could become a trend for ecological aware hobby gardeners and private households caring about the environment. If it would be feasible on a large scale remains unclear.

The high share of food production and agricultural activity in Germany especially the role of animal husbandry needs a more nuanced approach. Since this sector seems to be very important for the German economy, applying P containing fertilizer seems unavoidable. Nonetheless, mineral fertilizer should more and more be substituted by recovered P sources such as treated waste water sludge or bone meal and meat as suggested for other countries (e.g. Binder et al., 2009 for Switzerland) to decrease import dependencies. Now, the majority of abattoir waste is used in brown coal and coal-fired power plants and cement factories before the ashes and slags are being landfilled (Bolwerk & Richter, 2004). However, given the immense production of food for exports (2.5 times more than what they consume within the country), it is key to analyze the food production industry in detail to identify potential for reduction, substitution and recovery of current P inflows. Even though most P is exported again, the production process of agricultural goods (meat as well as vegetables or crops) goes hand in hand with leaches into the soil and the hydrosphere which is basically equivalent to P being lost in final sinks. Therefore, a more detailed analysis of the food production industry including the agricultural sector seems to be desirable.

Germany has developed regions specialized in specific industries, partly because of the geological and geographical conditions. It is highly plausible that different regions face different challenges in coping with P use and recovery potential as pointed out for Denmark by Klinglmair et al. (2015). Therefore, research on regional level seems to offer better insight in specific targets to optimize P use. Furthermore, most data especially data on agriculture, waste management and waste water management is available on state level.

However, the quality of P plays an important role especially in the chemical and refining industry. One has to be careful not to be carried away by focusing on reuse potentials but keep in mind that quality matters.

Despite the awareness of Germany of the finite character of P and its necessity for the German economy, it is surprising that data availability is still such a big issue. Most statistics that are currently available are meant for an economic analysis instead of an analysis in resource management. Even though data is collected for all federal states and listed separately, data on P flows by treatment method e.g. in waste management or waste water management is not available. However, this analysis would be interesting and help to better understand the applicability of certain P recovery technologies. Furthermore, data on pesticides was not available in the specifications necessary for this type of analysis. Even though data on the mass of herbicides is available, information of the chemical composition is missing which makes calculating the P load impossible. In this case the information gap had to be filled with data for Austria by Egle et al. (2014a) and multiplied by ten which is barely an approximation to the real value. Unfortunately, most of the flows with high P loads had to be taken from literature such as data used in Gethke-Albinus (2012) or by Kratz et al. (2014) – even for flows in the agricultural sector, where, in general, high-quality data is available but most of it was not suited for this type of analysis. Sometimes amounts are given in monetary terms instead of masses, or flows are not listed in detail but only in aggregates which makes the calculation of the P load difficult given that different materials exhibit different P concentrations. This lack of current, available data, is represented in the high uncertainties of flows and stocks.

To improve this P budget, so that it could serve to monitor P management in Germany, a more detailed presentation, especially with regard to the utilization of waste groups, is necessary. Exact and detailed data is the basis of any good analysis, the uncertainties of these flows could be minimized and the modelled budget would come even closer to real values. Further research should be undertaken to analyze regional differences and challenges regarding P optimization as well as industry specific investigation e.g. in food production.

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Phosphorus concentrations

Table 5: Table farm manure according to Egle et al. (2014a) with data from BMLFUW (2006).

animal species	kg P / stable place / year	animal species	kg P / stable place / year
horses (equids)		**pigs**	
		piglets up to 20 kg	0.9
small horses 0.5-3 years	2	young pigs 20 - 50 kg	1.9
> 3 years plus foals up to 0.5 years	2.3	fattening pigs 50 - 80 kg	1.9
small horses over 300 kg - "Haflinger"		fattening pigs 80 - 110 kg	1.9
0.5-3 years	3.8	fattening pigs greater than 110 kg	1.9
> 3 years	4.5	breeding pig 50 kg and more	
horses		guys, never covered	4.6
0.5-3 years	6.8	guided walks for the first time	4.6
> 3 years	8	mature sows, covered	4.6
cattle		older sows, not covered	4.6
young cattle under 1 year		boars	5.4
calves weighing up to 300 kg	3.1	**sheep**	
other calves and young cattle, male	5.9	ewes and lambs	1.7
other calves and young cattle, female	5.9	other sheep	0.9
juvenile 1 to under 2 years		**goats**	
bulls and oxen	8.6	goats that have already kidded	
battle heifers	8.6	and covered goats	2
working and breeding calves	8.6	other goats	1
cattle 2 years and older		**chickens**	
bulls and oxen	10.8	chicks for laying, laying hens	0.1
battle heifers	11.1	boiled chicken and chicken	0.1
working and breeding calves	11.1	**turkeys**	0.3
dairy cows	15.2	other poultry	0.1
other cows	9.3	framed vention	2.1

Table 6: Table food & feed according to Egle et al. (2014a) with data from Kroiss et al. (1998) and Zessner und Lampert (2002).

animal foods					
animals incl. bones	**P_{min} in %**	**P_{max} in %**	**milk products**	**P_{min} in %**	**P_{max} in %**
beef and veal	1.00	1.20	raw milk	0.09	0.10
pig	1.00	1.20	raw milk TM	0.69	0.77
sheep and goat	1.00	1.20	drinking milk	0.09	0.09
horse	1.00	1.20	full, skimmed milk powder	0.02	0.02
intestines	0.27	0.34	cream	0.16	0.41
poultry	0.18	0.21	butter	0.16	0.41
other meat	1.00	1.20	cheese spread	0.71	1.00
eggs	0.13	0.20	cheese	0.54	0.84
fish	0.14	0.30	whey	0.52	0.52
vegetable foods					
wheat	0.33	0.35	oilseeds in general	0.50	0.70
spelt	0.33	0.35	sunflowers	0.70	0.70
rye	0.33	0.35	soybean	0.48	0.48
oats	0.33	0.35	sugar beet	0.04	0.04
winter barley	0.33	0.35	fodder beet	0.03	0.04
spring barley	0.33	0.35	linseed		
grain maize	0.28	0.35	oil pumpkin		
triticale	0.33	0.35	poppy	0.50	0.70
summer cereals	0.33	0.35	legumes	0.48	0.48
winter cereals	0.33	0.35	grain peas	0.48	0.48
other cereals	0.33	0.35	field bean	0.52	0.52
rice	0.12	0.22	**by-products industry**		
other field fodder construction	0.07	0.07	by-products of milling industry	0.807	1.295
wine (grapes)	0.11	0.11	by-products of brewery	0.15	0.43
wine incl. juices & alcohol products	0.04	0.04	by-products of the distillery	0.025	2.073

brewing bar for beer	0.33	0.35	by-products of starch production	0.12	0.85
durum wheat	0.33	0.35	by-products of sugar production	0.02	0.09
vegetables	0.40	0.48			
winter rapeseed for oil production	0.50	0.79	by-products of oil production	0.52	0.67
summer raps and rakes	0.00	0.00	processing of sea animals	3	4
potato	0.05	0.10	processing of farm animals	2	3
tomatoes	0.05	0.10			
fruit in general	0.01	0.02	animal fats and oils	0.02	0.02
feedstuff					
more time meadows	0.41	0.41	temporary grassland	0.07	0.29
culture pastures	0.41	0.41	Straw and chaff	0.081	0.081
one time meadows	0.27	0.27	silage maize	0.07	0.09
pastures	0.32	0.32	green corn	0.07	0.08
mountain pastures	0.27	0.27	fodder beet	0.03	0.04
red clover & other clover	0.06	0.06	barley without malting	0.33	0.35
Lucerne	0.06	0.09	leaves and heads	0.25	0.25
clover	0.06	0.07			

Table 7: Table organic waste according to Egle et al. (2014a)

waste water sludge and ashes	**P_{min} in %**	**P_{max} in %**	**references**
waste water sludge communal	2.5	2.8	Scharf et al.,1997; Aichberger,1991;ÖWAV RB 1
ash municipal waste water sludge	7.5	8.5	Cornel, 2002; Mattenberger et al., 2008
ash industrial waste water sludge	1	1	Egle et al., 2014a
animal by-products			
carcass meal	5.2	6	Lettner et al., 1998; UBA, 2001
slaughterhouse waste	0.15	0.2	Kroiss et al., 1998
waste processing	4.5	5	UBA, 2001
kitchen dishwashing substance	0.09	0.14	Hoppenheidt et al., 2000
kitchen food waste dry substance	0.3	0.66	Hoppenheidt et al., 1998
biogenic waste and compost			
biogenic waste household	0.1	0.22	Binder et al., 2009; EPEA, 2008
biogenic waste green material	0.1	0.14	Binder et al., 2009; EPEA, 2008
market waste	0.015	0.03	KGVÖ, o.J.
composting in house gardens	0.1	0.14	Binder et al., 2009; EPEA, 2008
garden parking waste, road maintenance green	0.096	0.122	Binder et al., 2009; EPEA, 2008
cemetery waste	0.096	0.122	Binder et al., 2009; EPEA, 2008
compost end product	0.22	0.32	UBA-Deutschland, 2010; ÖPUL, 2000; KGVÖ oJ
municipal waste			
residual waste	0.78	1.06	Skutan and Brunner, 2006
wastepaper	0.005	0.007	Binder et al., 2009; EPEA, 2008
old wood	0.013	0.014	Kroiss et al., 1998
old cars	0.04	0.04	Kroiss et al., 1998
biogas input			
corn silage	0.07	0.09	ÖPUL, 2000; LFL, 2010
pig manure	0.11	0.17	ÖPUL, 2000; LFL, 2010
cattle slurry	0.07	0.11	ÖPUL, 2000; LFL, 2010
bio-waste	0.1	0.22	Binder et al., 2009; EPEA, 2008
leftovers	0.09	0.14	Binder et al., 2009; EPEA, 2008
grass silage	0.13	0.13	ÖPUL, 2000; LFL, 2010

whey, permeate	0.03	0.03	Kroiss et al., 1998
rest	0.07	0.11	Egle et al., 2014a
cattle dung	0.13	0.17	ÖPUL, 2000; LFL, 2010
Sudan grass	0.04	0.04	ÖPUL, 2000; LFL, 2010
pressed pulp	0	0	ÖPUL, 2000; LFL, 2010
sweet sorghum	0.04	0.04	ÖPUL, 2000; LFL, 2010
Lucerne	0.06	0.09	ÖPUL, 2000; LFL, 2010
rye silage	0.13	0.14	ÖPUL, 2000; LFL, 2010
branches and bark	0.033	0.044	Kroiss et al., 1998
stem and bark	0.013	0.014	Kroiss et al., 1998
root	0.045	0.063	Kroiss et al., 1998
leaves / needles	0.07	0.1	Kroiss et al., 1998
ash cogeneration	1	1.4	Schiemenz et al., 2010, Petterson, 2008, Demeyer et al., 2000

Calculations

Table 8: Flows of the German phosphorus budget with name, source and destination processes and values.

Process	Flow	Flow name	Source process	Destination Process	Mass flow [t/a]	Mass flow (calculated) [t/a]
Process name:	**agriculture - animal husbandry**					
Input						
P 1	F 2.1	non-salable feed	P 2, agriculture - crop farming	P 1, agriculture - animal husbandry	290,000±33%	290,000±33%
P 1	F 1.1	import living animals		P 1, agriculture - animal husbandry	9,200±46%	9,200±46%
P 1	F 5.6	salable feed	P 5, refining industry (food, feed, fertilizer)	P 1, agriculture - animal husbandry	51,000±33%	52,000±32%
Output						
P 1	F 1.3	manure	P 1, agriculture - animal husbandry	P 2, agriculture - crop farming	270,000±79%	270,000±79%
P 1	F 1.6	fallen animals	P 1, agriculture - animal husbandry	P 8, waste management	4,300±54%	4,300±54%
P 1	F 1.5	fecal biogas substrates	P 1, agriculture - animal husbandry	P9,biogas plants	1,400±120%	1,400±114%
P 1	F 1.2	export living animals	P 1, agriculture - animal husbandry		3,800±45%	3,800±45%
P 1	F 1.4	animal products	P 1, agriculture - animal husbandry	P 5, refining industry (food, feed, fertilizer)	110,000±44%	98,000±46%
Process name:	**agriculture - crop farming**					
Input						
P 2	F 1.3	manure	P 1, agriculture - animal husbandry	P 2, agriculture - crop farming	270,000±79%	270,000±79%
P 2	F 5.7	mineral fertilizer (agriculture)	P 5, refining industry (food, feed, fertilizer)	P 2, agriculture - crop farming	120,000±33%	130,000±30%
P 2	F 8.2	waste water sludge CF	P 8, waste management	P 2, agriculture - crop farming	12,000±36%	12,000±36%
P 2	F 4.3	pesticides	P 4, chemical industry	P 2, agriculture - crop farming	150±104%	150±108%
P 2	F 9.1	digestate	P9,biogas plants	P 2, agriculture - crop farming	570±15%	570±15%
P 2	F 8.5	compost and bone meal cf	P 8, waste management	P 2, agriculture - crop farming	38,000±15%	38,000±15%
Output						

P 2	F 2.1	non-salable feed	P 2, agriculture - crop farming	P 1, agriculture - animal husbandry	290,000±33%	290,000±33%
P 2	F 2.4	vegetable biogas substrates	P 2, agriculture - crop farming	P9,biogas plants	3,700±110%	3,700±71%
P 2	F 2.2	vegetable products	P 2, agriculture - crop farming	P 5, refining industry (food, feed, fertilizer)	170,000±32%	160,000±33%
P 2	F 2.3	erosion farming	P 2, agriculture - crop farming	P 10, hydro-sphere	24,000±33%	24,000±33%
Process name:	**chemical industry**					
Input						
P 4	F 4.1	import chemicals		P 4, chemical industry	24,000±46%	47,000±8%
P 4	F 5.12	refined P-containing materials	P 5, refining industry (food, feed, fertilizer)	P 4, chemical industry	5,100±46%	6,100±38%
Output						
P 4	F 4.2	export chemicals	P 4, chemical industry		47,000±5%	46,000±5%
P 4	F 4.5	waste water of chemical industry	P 4, chemical industry	P 7, waste water management	1,300±20%	1,300±20%
P 4	F 4.4	detergents	P 4, chemical industry	P 6, household (and infrastructure)	7,000±35%	5,900±40%
P 4	F 4.3	pesticides	P 4, chemical industry	P 2, agriculture - crop farming	150±104%	150±108%
Process name:	**forestry and other soils**					
Input						
P 3	F 6.3	used paper	P 6, household (and infrastructure)	P 3, forestry and other soils	900±64%	900±64%
P 3	F 3.1	import of wood and paper		P 3, forestry and other soils	59,000±157%	59,000±157%
P 3	F 8.1	substrate landscaping	P 8, waste management	P 3, forestry and other soils	2,400±64%	2,400±64%
P 3	F 8.3	untreated wood waste	P 8, waste management	P 3, forestry and other soils	2,700±43%	2,700±43%
Output						
P 3	F 3.2	export of wood and paper	P 3, forestry and other soils		56,000±157%	56,000±157%
P 3	F 3.3	paper	P 3, forestry and other soils	P 6, household (and infrastructure)	1,200±64%	1,200±64%
P 3	F 3.4	wood goods	P 3, forestry and other soils	P 6, household (and infrastructure)	52±158%	52±158%
P 3	F 3.5	wood waste	P 3, forestry and other soils	P 8, waste management	21±30%	21
Process name:	**household (and infrastructure)**					
Input						

P 6	F 5.4	food	P 5, refining industry (food, feed, fertilizer)	P 6, household (and infrastructure)	82,000±105%	66,000±27%
P 6	F 8.4	compost hh	P 8, waste management	P 6, household (and infrastructure)	3,300±15%	3,300±15%
P 6	F 4.4	detergents	P 4, chemical industry	P 6, household (and infrastructure)	7,000±35%	5,900±40%
P 6	F 3.3	paper	P 3, forestry and other soils	P 6, household (and infrastructure)	1,200±64%	1,200±64%
P 6	F 3.4	wood goods	P 3, forestry and other soils	P 6, household (and infrastructure)	52±158%	52±158%
Output						
P 6	F 6.2	residual waste	P 6, household (and infrastructure)	P 8, waste management	10,000±61%	10,000±59%
P 6	F 6.3	used paper	P 6, household (and infrastructure)	P 3, forestry and other soils	900±64%	900±64%
P 6	F 6.4	biogenic waste	P 6, household (and infrastructure)	P 8, waste management	12,000±93%	13,000±86%
P 6	F 6.1	municipal waste water	P 6, household (and infrastructure)	P 7, waste water management	57,000±33%	52,000±24%
Process name:	**hydro-sphere**					
Input						
P 10	F 2.3	erosion farming	P 2, agriculture - crop farming	P 10, hydro-sphere	24,000±33%	24,000±33%
P 10	F 7.2	purified waste water	P 7, waste water management	P 10, hydro-sphere	8,100±46%	8,400±44%
P 10	F 7.3	extraneous water	P 7, waste water management	P 10, hydro-sphere	670±15%	670±15%
P 10	F 7.4	rain-water overflow	P 7, waste water management	P 10, hydro-sphere	4,900±46%	5,000±45%
Output						
P 10	F 10.1	water export	P 10, hydro-sphere		38,000±141%	38,000±23%
Process name:	**refining industry (food, feed, fertilizer)**					
Input						
P 5	F 5.1	import highly P-containing materials (e.g. fertilizer)		P 5, refining industry (food, feed, fertilizer)	260,000±46%	200,000±40%
P 5	F 5.2	import food		P 5, refining industry (food, feed, fertilizer)	20,000±62%	19,000±64%
P 5	F 5.3	import feed		P 5, refining industry (food, feed, fertilizer)	32,000±33%	31,000±34%
P 5	F 2.2	vegetable products	P 2, agriculture - crop farming	P 5, refining industry (food, feed, fertilizer)	170,000±32%	160,000±33%
P 5	F 1.4	animal products	P 1, agriculture - animal husbandry	P 5, refining industry (food, feed, fertilizer)	110,000±44%	98,000±46%

Output

P 5	F 5.8	export mineral fertilizer	P 5, refining industry (food, feed, fertilizer)		23,000±33%	23,000±33%
P 5	F 5.9	export food	P 5, refining industry (food, feed, fertilizer)		160,000±33%	170,000±29%
P 5	F 5.10	export feed	P 5, refining industry (food, feed, fertilizer)		4,600±33%	4,600±33%
P 5	F 5.4	food	P 5, refining industry (food, feed, fertilizer)	P 6, household (and infrastructure)	82,000±105%	66,000±27%
P 5	F 5.5	refining waste	P 5, refining industry (food, feed, fertilizer)	P 8, waste management	36,000±48%	37,000±46%
P 5	F 5.7	mineral fertilizer (agriculture)	P 5, refining industry (food, feed, fertilizer)	P 2, agriculture - crop farming	120,000±33%	130,000±30%
P 5	F 5.11	refine industrial waste water	P 5, refining industry (food, feed, fertilizer)	P 7, waste water management	14,000±5%	14,000±5%
P 5	F 5.6	salable feed	P 5, refining industry (food, feed, fertilizer)	P 1, agriculture - animal husbandry	51,000±33%	52,000±32%
P 5	F 5.12	refined P-containing materials	P 5, refining industry (food, feed, fertilizer)	P 4, chemical industry	5,100±46%	6,100±38%

Process name: waste management

Input

P 8	F 6.2	residual waste	P 6, household (and infrastructure)	P 8, waste management	10,000±61%	10,000±59%
P 8	F 6.4	biogenic waste	P 6, household (and infrastructure)	P 8, waste management	12,000±93%	13,000±86%
P 8	F 5.5	refining waste	P 5, refining industry (food, feed, fertilizer)	P 8, waste management	36,000±48%	37,000±46%
P 8	F 1.6	fallen animals	P 1, agriculture - animal husbandry	P 8, waste management	4,300±54%	4,300±54%
P 8	F 7.1	waste water sludge	P 7, waste water management	P 8, waste management	48,000±36%	53,000±24%
P 8	F 3.5	wood waste	P 3, forestry and other soils	P 8, waste management	21±30%	21
P 8	F 9.2	solid biogas residue	P9,biogas plants	P 8, waste management	4,500±68%	4,500±56%

Output

P 8	F 8.4	compost hh	P 8, waste management	P 6, household (and infrastructure)	3,300±15%	3,300±15%
P 8	F 8.3	untreated wood waste	P 8, waste management	P 3, forestry and other soils	2,700±43%	2,700±43%
P 8	F 8.1	substrate landscaping	P 8, waste management	P 3, forestry and other soils	2,400±64%	2,400±64%
P 8	F 8.2	waste water sludge CF	P 8, waste management	P 2, agriculture - crop farming	12,000±36%	12,000±36%

P 8	F 8.5	compost and bone meal cf	P 8, waste management	P 2, agriculture - crop farming	38,000±15%	38,000±15%
Process name: waste water management						
Input						
P 7	F 4.5	waste water of chemical industry	P 4, chemical industry	P 7, waste water management	1,300±20%	1,300±20%
P 7	F 5.11	refine industrial waste water	P 5, refining industry (food, feed, fertilizer)	P 7, waste water management	14,000±5%	14,000±5%
P 7	F 6.1	municipal waste water	P 6, household (and infrastructure)	P 7, waste water management	57,000±33%	52,000±24%
Output						
P 7	F 7.1	waste water sludge	P 7, waste water management	P 8, waste management	48,000±36%	53,000±24%
P 7	F 7.2	purified waste water	P 7, waste water management	P 10, hydro-sphere	8,100±46%	8,400±44%
P 7	F 7.3	extraneous water	P 7, waste water management	P 10, hydro-sphere	670±15%	670±15%
P 7	F 7.4	rain-water overflow	P 7, waste water management	P 10, hydro-sphere	4,900±46%	5,000±45%
Process name: biogas plants						
Input						
P9	F 1.5	fecal biogas substrates	P 1, agriculture - animal husbandry	P9,biogas plants	1,400±120%	1,400±114%
P9	F 2.4	vegetable biogas substrates	P 2, agriculture - crop farming	P9,biogas plants	3,700±110%	3,700±71%
Output						
P9	F 9.2	solid biogas residue	P9,biogas plants	P 8, waste management	4,500±68%	4,500±56%
P9	F 9.1	digestate	P9,biogas plants	P 2, agriculture - crop farming	570±15%	570±15%

Table 9: Data and the calculations of flow values and their uncertainty factors

		flow in t/yr						P concentration		A1	A2							uncertainty	±
Flow	flow name	2014	2015	2016	mean	UL_1	UF_1	P_min %	P_max %	P_min in t	P_max in t	m=(A1*A2)^(-1/2)	UL_2	UF_2	UF_12	IS=m*(UF_12-1)^2	UF_flow		
F 1.1	import living animals											9212,95					1,46	45,9%	4228,62
	horses	939,00	944,00	746,00	876,33	1	1,11	1,00%	1,20%	8,76	10,52	9,60	2,28	1,45	1,46	2,03			
	cattle	27176,00	19337,00	16884,00	21132,33	1	1,11	1,00%	1,20%	211,32	253,59	231,49	2,28	1,45	1,46	49,03			
	pigs	789697,00	763747,00	801648,00	785030,67	1	1,11	1,00%	1,20%	7850,31	9420,37	8599,58	2,28	1,45	1,46	1821,51			
	sheep	3035,00	3324,00	5044,00	3801,00	1	1,11	1,00%	1,20%	38,01	45,61	41,64	2,28	1,45	1,46	8,82			
	poultry	156565,00	156731,00	175115,00	162803,67	1	1,11	0,18%	0,21%	293,05	341,89	316,53	2,20	1,41	1,42	56,49			
	other	1394,00	1264,00	1206,00	1288,00	1	1,11	1,00%	1,20%	12,88	15,46	14,11	2,28	1,45	1,46	2,99			
F 1.2	export living animals											3814,61					1,45	45,1%	1720,64
	horses	2337,00	2771,00	2841,00	2649,67	1	1,11	1,00%	1,20%	26,50	31,80	29,03	2,28	1,45	1,46	6,15			
	cattle	99046,00	108464,00	104839,00	104116,33	1	1,11	1,00%	1,20%	1041,16	1249,40	1140,54	2,28	1,45	1,46	241,58			
	pigs	207179,00	157100,00	95415,00	153231,33	1	1,11	1,00%	1,20%	1532,31	1838,78	1678,57	2,28	1,45	1,46	355,54			
	sheep	596,00	379,00	312,00	429,00	1	1,11	1,00%	1,20%	4,29	5,15	4,70	2,28	1,45	1,46	1,00			
	poultry	470150,00	523618,00	481410,00	491726,00	1	1,11	0,18%	0,21%	885,11	1032,62	956,02	2,20	1,41	1,42	170,63			
	other	441,00	596,00	541,00	526,00	1	1,11	1,00%	1,20%	5,26	6,31	5,76	2,28	1,45	1,46	1,22			
F 1.3	manure											265159,18					1,79	78,9%	209154,05
	liquid manure in m^3 = t																		
	(approx. 1/2 of this is cattle slurry)		104019650,00		104019650,00	2	1,33	0,07%	0,11%	72813,76	114421,62	91276,87	2,76	1,76	1,82	61988,07			
	(approx. 1/2 of this is pig slurry)		104019650,00		104019650,00	2	1,33	0,11%	0,17%	114421,62	176833,41	142244,73	2,73	1,74	1,81	92906,77			
	solid manure in t		21199800,00		21199800,00	1	1,11	0,13%	0,17%	27559,74	36039,66	31515,77	2,48	1,55	1,57	10069,49			
	poultry droppings in t		1161400,00		1161400,00	1	1,11	0,1 kg	0,1 kg	116,14	127,75	121,81	1,97	1,32	1,33	13,62			
F 1.4	animal products											107595,18					1,44	43,6%	46947,57
	cattle	1132645,00	1132880,00	1147073,00	1137532,67	1	1,11	1,00%	1,20%	11375,33	13650,39	12461,05	2,28	1,45	1,46	2639,42			
	pigs	5516292,00	5566324,00	5581376,00	5554664,00	1	1,11	1,00%	1,20%	55546,64	66655,97	60848,30	2,28	1,45	1,46	12888,52			
	sheep	19812,00	20454,00	21160,00	20475,33	1	1,11	1,00%	1,20%	204,75	245,70	224,30	2,28	1,45	1,46	47,51			
	goat	438,00	425,00	416,00	426,33	1	1,11	1,00%	1,20%	4,26	5,12	4,67	2,28	1,45	1,46	0,99			
	horse	2337,00	2397,00	2193,00	2309,00	1	1,11	1,00%	1,20%	23,09	27,71	25,29	2,28	1,45	1,46	5,36			
	poultry	1526310,60	1520442,50	1526774,30	1524509,13	1	1,11	0,18%	0,21%	2744,12	3201,47	2963,98	2,20	1,41	1,42	529,01			
	fish			32416,60	32416,60	1	1,11	0,14%	0,30%	45,38	97,25	66,43	3,07	2,07	2,07	76,71			
	eggs (est. 60 g per egg)	693420,00		718721,20	706070,60	1	1,11	0,13%	0,20%	917,89	1412,14	1138,50	2,73	1,73	1,74	626,49			
	milk	31389000,00	31495000,00	31550000,00	31478000,00	1	1,11	0,09%	0,10%	28330,20	31478,00	29862,65	2,01	1,33	1,35	3670,87			
F 1.5	fecal biogas substrates	1240200,00			1240200,00	1	1,11	0,07%	0,17%	868,14	2108,34	1352,90	3,17	2,20	2,20	1948,70	2,20	120,0%	1623,70
F 1.6	fallen animals			425000,00	425000,00	1	1,11					4301,60		1,04	1,11	56,39	1,54	53,6%	2306,45
	15,5% bones			65875,00	65875,00	2	1,33	5,20%	6,00%	3425,50	3952,50	3679,58	2,16	1,39	1,51	962,35			
	84,5% rest			359125,00	359125,00	2	1,33	0,15%	0,20%	538,69	718,25	622,02	2,51	1,58	1,66	274,33			
F 2.1	non-salable feed					2	1,33					288000,00		1,04	1,33	31388,77	1,33	33,0%	95078,74
F 2.2	vegetable products											172272,86					1,32	32,1%	55223,30
	vegetables			3516305,10	3516305,10	1	1,11	0,40%	0,55%	14065,22	19339,68	16492,93	2,56	1,61	1,62	6379,70			
	fruit		9734624,00	10329127,00	10031875,50	1	1,11	0,01%	0,01%	1003,19	1103,51	1052,15	1,97	1,32	1,33	117,65			
	grain		48867000,00	42182900,00	45524950,00	1	1,11	0,33%	0,35%	150232,34	159337,33	154717,87	1,74	1,25	1,27	11204,67			
	wine		8872,80	9069,20	8971,00	1	1,11	0,11%	0,11%	9,87	9,96	9,91	0,88	1,10	1,14	0,21			
F 2.3	erosion farming					2	1,33					24063,00		1,04	1,33	2622,60	1,33	33,0%	7944,03
F 2.4	vegetable biogas substrates	2492900,00			2492900,00	1	1,11	0,10%	0,22%	2492,90	5484,38	3697,57	3,09	2,10	2,10	4480,76	2,10	110,1%	4070,37
F 3.1	import of wood and paper											59484,52					2,57	157,1%	93464,24
	import paper	11224000,00	11514000,00		11369000,00	1	1,11	0,01%	0,01%	568,45	795,83	672,60	2,59	1,63	1,64	276,99			
	import wood (est. 1.87 t per m^3 (r))	246092000,00	245718000,00		245905000,00	2	1,33	0,01%	0,04%	31967,65	108198,20	58811,92	3,40	2,54	2,58	146577,43			
F 3.2	export of wood and paper											55877,54					2,57	156,9%	87685,36
	export paper	13218000,00	13829000,00		13523500,00	1	1,11	0,01%	0,01%	676,18	946,65	800,06	2,59	1,63	1,64	329,48			
	export wood (est. 1.87 t per m^3 (r))	230384000,00	230197000,00		230290500,00	2	1,33	0,01%	0,04%	29937,77	101327,82	55077,48	3,40	2,54	2,58	137270,05			
F 3.3	paper	20546000,00	20829000,00		20687500,00	1	1,11	0,01%	0,01%	1034,38	1448,13	1223,89	2,59	1,63	1,64	504,01	1,64	64,2%	785,40
F 3.4	wood goods	215424,00	222530,00		218977,00	2	1,33	0,01%	0,04%	28,47	96,35	52,37	3,40	2,54	2,58	130,53	2,58	157,9%	82,68
F 3.5	wood waste	153200,00			153200,00	1	1,11	0,01%	0,01%	19,92	21,45	20,67	1,85	1,28	1,30	1,83	1,30	29,8%	6,16
F 4.1	import chemicals						1,04					24088,00		1,04	1,05	62,44	1,46	46,4%	11179,16
	import chemicals for detergents					2	1,33					5919,00	2,00	1,33	1,46	1274,87			
	import chemicals for HH					2	1,33					13103,00	2,00	1,33	1,46	2822,20			
	import phosphorous-containing materials for industry					2	1,33					5066,00	2,00	1,33	1,46	1091,14			
F 4.2	export chemicals						1,04					46582,00		1,04	1,05	120,74	1,05	5,1%	2371,57
	detergents					2	1,33					15015,00	2,00			15015,00			
	phosphorus industry					2	1,33					31567,00	2,00			31567,00			
F 4.3	pesticides					2	1,33					150,00	3,00	1,99	2,04	163,41	2,04	104,4%	156,56
F 4.4	detergents					1	1,11					7000,00	2,00	1,33	1,35	836,55	1,35	34,6%	2419,88
F 4.5	waste water of chemical industry					2	1,33					1300,00	2,00	1,33	1,46	280,00	1,20	20,0%	260,00
F 5.1	import highly P-containing materials (e.g. fertilizer)					2	1,33					258634,00		1,04	1,33	28188,21	1,46	46,4%	120031,14
	import rock phosphate					2	1,33					51175,00	2,00	1,33	1,46	11022,36			
	import phosphorous-containing materials					2	1,33					135843,00	2,00	1,33	1,46	29258,62			
	import mineral fertilizer					2	1,33					71616,00	2,00	1,33	1,46	15425,05			
F 5.2	import food						1,04					19859,11		1,04	1,05	51,47	1,62	62,0%	12309,69
	fish				800000,00	2	1,33	0,14%	0,30%	1120,00	2400,00	1639,51	3,07	2,07	2,12	2050,29			
	meat				1400699,60	2	1,33	1,00%	1,20%	14007,00	16808,40	15343,90	2,28	1,45	1,55	4721,21			
	processed meat				190874,10	2	1,33	1,00%	1,20%	1908,74	2290,49	2090,92	2,28	1,45	1,55	643,36			
	poultry				403649,70	2	1,33	0,18%	0,21%	726,57	847,66	784,78	2,20	1,41	1,52	215,31			
F 5.3	import feed				6600000,00	2	1,33	0,48%	0,48%	31680,00	31746,00	31712,98	0,21	1,05	1,33	3481,33	1,33	33,1%	10507,30
	soybeans				3200000,00	2	1,33	0,48%	0,48%	15360,00	15392,00	15375,99	0,21	1,05	1,33	1687,92			
	soy grits				3400000,00	2	1,33	0,48%	0,48%	16320,00	16354,00	16336,99	0,21	1,05	1,33	1793,41			
F 5.4	food											82028,00	2,00	1,33	2,05	90861,82	2,05	105,2%	86332,00
F 5.5	refining waste											35512,45	2,00	1,33	2,05	39336,88	1,48	47,9%	17007,95
	vegetables (18%)				632934,92	2	1,33	0,40%	0,55%	2531,74	3481,14	2968,73	2,56	1,61	1,69	1432,98			
	fruit (18%)				1805737,59	2	1,33	0,01%	0,01%	180,57	198,63	189,39	1,97	1,32	1,46	39,33			
	grain (18%)				8194491,00	2	1,33	0,33%	0,35%	27041,82	28680,72	27849,22	1,74	1,25	1,41	4686,99			
	wine (18%)				1614,78	2	1,33	0,11%	0,11%	1,78	1,79	1,78	0,88	1,10	1,34	0,21			
	abattoir waste			2600000,00	2600000,00	2	1,33	0,15%	0,20%	3900,00	5200,00	4503,33	2,51	1,58	1,66	1986,09			
F 5.6	salable feed						1,04					51000,00	2,00	1,33	1,33	5558,43	1,33	33,0%	16836,86
F 5.7	mineral fertilizer (agriculture)						1,04					124011,00	2,00	1,33	1,33	13515,81	1,33	33,0%	40940,31
F 5.8	export mineral fertilizer						1,04					23144,00	2,00	1,33	1,33	2522,44	1,33	33,0%	7640,63
F 5.9	export food						1,04					159147,00	2,00	1,33	1,33	17345,24	1,33	33,0%	52539,91
F 5.10	export feed						1,04					4610,00	2,00	1,33	1,33	502,44	1,33	33,0%	1521,92
F 5.11	refine industrial waste water						1,04					13583,00	2,00	1,33	1,33	1480,39	1,05	5,1%	691,53
	waste water fertilizer						1,04					9508,00		1,04	1,05	24,64			
	industrial waste water						1,04					4075,00		1,04	1,05	10,56			
F 5.12	refined P-containing materials					2	1,33					5066,00	2,00	1,33	1,46	1091,14	1,46	46,4%	2351,11
F 6.1	municipal waste water						1,04					56568,00	2,00	1,33	1,33	6165,28	1,33	33,0%	18675,05
F 6.2	residual waste	1121700,00			1121700,00	1	1,11	0,78%	1,06%	8749,26	11890,02	10199,45	2,54	1,60	1,61	3781,84	1,61	60,9%	6210,69
F 6.3	used paper	15102000,00	15221000,00		15161500,00	1	1,11	0,01%	0,01%	758,08	1061,31	896,97	2,59	1,63	1,64	369,38	1,64	64,2%	575,61
F 6.4	biogenic waste											12302,10					1,93	92,7%	11409,39
	kitchen waste	4104600,00			4104600,00	1	1,11	0,10%	0,22%	4104,60	9030,12	6088,11	3,09	2,10	2,10	7377,65			
	kitchen waste gastro	543400,00			543400,00	1	1,11	0,10%	0,22%	543,40	1195,48	805,99	3,09	2,10	2,10	976,71			
	garden waste	4570600,00			4570600,00	1	1,11	0,10%	0,14%	4570,60	6398,84	5408,01	2,59	1,63	1,64	2227,09			
F 7.1	waste water sludge	1802988,00	1803087,00		1803037,50	1	1,11	2,50%	2,80%	45075,94	50485,05	47703,89	2,05	1,35	1,36	6288,04	1,36	36,3%	17319,47
F 7.2	purified waste water					2	1,33					8127,00	2,00	1,33	1,46	1750,44	1,46	46,4%	3771,71
F 7.3	extraneous water					1	1,11					670,70	1,00	1,11	1,15	15,85	1,15	15,4%	103,10
F 7.4	rain-water overflow					2	1,33					4900,00	2,00	1,33	1,46	1055,39	1,46	46,4%	2274,07
F 8.1	substrate landscaping	216148,00	190127,00		203137,50	1	1,11	1,00%	1,40%	2031,38	2843,93	2403,56	2,59	1,63	1,64	989,82	1,64	64,2%	1542,43
F 8.2	waste water sludge cf	470882,00	427736,00		449309,00	1	1,11	2,50%	2,80%	11232,73	12580,65	11887,60	2,05	1,35	1,36	1566,95	1,36	36,3%	4315,93
F 8.3	untreated wood waste	20009000,00	20009000,00		20009000,00	2	1,33	0,01%	0,01%	2601,17	2801,26	2699,36	1,85	1,28	1,43	498,34	1,43	43,0%	1159,83
F 8.4	compost hh					1	1,11					3300,00	1,00	1,11	1,15	77,97	1,15	15,4%	507,26
F 8.5	compost and bone meal cf					1	1,11					38100,00					1,15	15,4%	5856,50
	bone meal					1	1,11					33000,00	1,00	1,11	1,15	779,72			
	copost cf					1	1,11					5100,00	1,00	1,11	1,15	120,50			
F 9.1	digestate					1	1,11					572,76	1,00	1,11	1,15	13,53	1,15	15,4%	88,04
	fecal biogas substrates											1352,90			1,57	437,86			
	vegetable biogas substrates											3697,57			1,50	907,10			
	solid biogas residue											4477,71			1,23	243,09			
F 9.2	solid biogas residue		1687600,00		1687600,00	1	1,11	0,22%	0,32%	3712,72	5400,32	4477,71	2,65	1,67	1,68	2088,22	1,68	68,3%	3057,85
F 10.1	water export											37760,70		1,04	2,00	37809,64	2,00	100,1%	37785,16
Stocks	**process name**											**P stock in t**						**uncertainty**	**±**
S1	animal husbandry					2	1,33					228098,20	2,00	1,33	1,46	49129,06	1,46	46,4%	105859,58
S2	crop farming					3	1,99					121466190,00	3,00	1,99	2,40	238485962,69	2,40	140,1%	170199827,43
S3	forestry and other soils					3	1,99					62939520,00	3,00	1,99	2,40	123575062,48	2,40	140,1%	88191581,89