Can waste equal food?

Exploring the urban opportunities and limitations in advancing a closed loop practice of phosphorus; the case of Wageningen, the Netherlands.

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WAGENINGEN UR
For quality of life

Henk Wildschut,
Khouribga, phosphate mine / Barneveld, biological chickens 2012

Colophon
How can waste equal food?
Exploring the urban opportunities and limitations for a closed loop practice of phosphorus, the case of Wageningen, the Netherlands.

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This MSc thesis is part of a combined thesis project with Timo Eckhardt, who has written an MSc thesis for the Environmental Policy Group, Wageningen, titled: *"The Binding Potential of P. An Analysis of the Governance Network for Phosphorus Recycling and Reuse in Wageningen, the Netherlands."*

"There is no guano comparable in fertility with the detritus of a capital. A great city is the most mighty of dung-makers. Certain success would attend the experiment of employing the city to manure the plain. If our gold is manure, our manure, on the other hand, is gold."

Victor Hugo, Les Miserables,1862

"The present moment is the substance with which the future is made. Therefore, the best way to take care of the future is to take care of the present moment."

Thích Nhất Hạnh, Art of Mindful Living: How to Bring Love, Compassion, and Inner Peace Into Your Daily Life, 2000

Abstract

Phosphorus (P) plays a key and unique role in the growth and functioning of life on earth, yet it is marked by critical concerns such as (economic) scarcity and a growing demand for P that needs to be met. With P being an important component of fertilisers, combined with a growing world population, access to sufficient P is crucial for food security. Despite these concerns, large amounts of P are currently (unnecessarily) lost and do not return to the human food system. Moreover, losses of P into water bodies cause eutrophication that has detrimental effects on ecological systems. Overall, these issues clearly illustrate a need for sustainable P management. There has been much focus on the agricultural sector, yet the role and contribution of urban areas in these global P issues should not be overlooked. With most of the worldwide population being urban dwellers, it is urban areas that drive the demand for food production (and subsequently P) and therefore become so-called 'P hotspots'.

This thesis therefore examines infrastructural limitations and opportunities for (small) urban areas to foster P reuse (compost and sludge from anaerobic digestion) and recycling (struvite) through its waste management system - consisting of wastewater (WW) and municipal solid waste (MSW) - that determines the flow of P. In doing so, the city of Wageningen, the Netherlands was chosen as a case-study and limited to P found in food related flows only, which represents the largest flow of P in an urban area. The research conducted was two-fold. First, a quantitative substance flow analysis (SFA) was used to identify current P losses from the urban system. Subsequently, feasible alternative strategies (from the perspective of the municipality) for altering the waste management system to enhance P reuse and recycling were researched and their impact was estimated. By doing so, limitations and opportunities for the municipality to increase P reuse and recycling could be identified. Main data collection methods were literature search, thirteen in-depth interviews, other personal communication (email and phone) with thirty-two actors as well as two site visits.

The SFA of Wageningen with the base year of 2012 shows that the distribution of P flows (in t/yr) in the waste stream was nearly equal for WW and MSW. Of the total P input into Wageningen, which amounted to 51.2 t P/yr, there was no P recycling, and P reuse accounted for 6 % of total P input (of which 80 % was due to pet flows). This means 94 % of all P input is lost. The SFA results show the importance of considering P flows related to pets in urban areas (accounted for 24 % of total P input). The proposed strategies enhance P reuse and recycling only about 1 t P/yr.

Limitations and opportunities were found to be determined by the level of influence, incentive and capacity of the municipality to act. On both the national and local level, the strongest opportunities for the municipality appeared to reside in MSW (enhancing the separation rate of organic waste). On a national level, market and regulative forces push for organic waste separation and thereby provide incentive to take action on an urban level. On the local level, the municipality has more influence on MSW management in comparison to WW, where this proved to be limited. Furthermore, results show that it could be beneficial for the municipality to improve its connectedness to other actors (on regional or national level) for either collaboration or knowledge sharing. This connectedness can enhance the overall ability of (especially small) municipalities to implement appropriate measures on the level of infrastructure to foster P reuse and recycling. Overall, this thesis shows that urban areas definitely have a role (and responsibility) to play given the fact that most of the P (from food) is still being lost.

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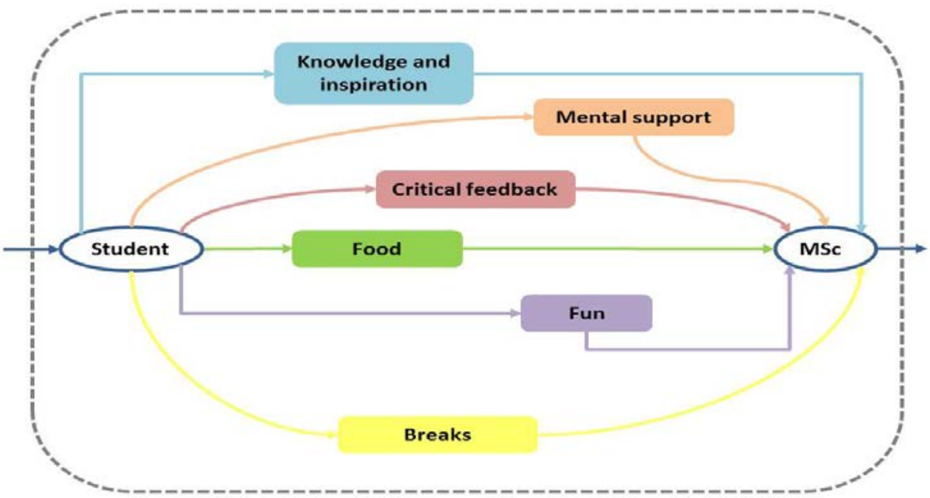

Process of Alison Jenkins, MUE program, Wageningen University, 2011-2014

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List of abbreviations

ATP	Adenosine triphosphate
Bio-P	Biological removal of phosphorus (from wastewater)
BO	Businesses and Offices
BW	Black water
Cyclic-ADM	Cyclic-adenosine monophosphates
DESAR	Decentralised Sanitation and Reuse
DNA	Deoxyribonucleic acid
DRANCO	DRy ANaerobic COmposting
EU	European Union
ESPP	European Sustainable Phosphorus Platform
ETE	Sub-Department of Environmental Technology
FAO	Food and Agriculture Organization
GFT	Groente- Fruit- en Tuinafval
GW	Grey water
LeAF	Lettinga Associate Foundation
MFA	Material Flow Analysis
MSW	Municipal solid waste
NIOO-KNAW	Netherlands Institute of Ecology
NP	Nutrient Platform
P	Phosphorus
PWVE	Platform Water Vallei en Eem
QSR	Quick Service Restaurant
SFA	Substance Flow Analysis
SNA	Social Network Analysis
STPP	Sodium trypolyphosphate
U.S.	United States of America
U.S.G.S	US Geological Survey
VA	Vereniging Afvalbedrijven
VOCs	Volatile organic compounds
WTO	World Trade Organisation
WUR	Wageningen University and Research Centre
WW	Wastewater
WWII	World War II
WWTP	Wastewater treatment plant

Unit Measures Abbreviations

g/L	gram per litre
kg/c	kilogram per capita
kg/L	kilogram per litre
Kt	kilo tonne
L	litre
m	metre
mg/day	milligram per day
mg/kg	milligram per kilogram
mg/L	milligram per litre
mg P/day	milligram of phosphorus per day
Mkg	million kg
Mt	million tonne
P/ha	phosphorus/hectare
t	tonne
t P/yr	tonne of phosphorus per year
t/a	tonne/annum
t/yr	tonne/year

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1. Introduction

1.1. Problem introduction

Phosphorus (P) is a nutrient essential to life on earth, since it is a necessary component for plants, animals and humans to function and grow (Jasinski, 2004). For instance, our DNA (partly) consists of this chemical element (Emsley, 2000; Ghosh and Bansal, 2003), cells require it to form their components and for gaining energy, and P also plays a part in the release of hormones (Emsley, 2000; Schröder et al., 2010). The intake of P for humans is through the food system. This food system starts with fertile soil, containing a sufficient amount of available P for plant uptake through their roots. It is therefore not surprising that P forms a crucial component of agricultural fertilisers, together with nitrogen and potassium (Cordell et al., 2009). When crops are harvested for food consumption, P is consumed by animals and humans, by which it is mostlyy excreted (Schröder et al., 2010).

Whilst the use and application of P goes far beyond fertilisers alone[1], around ninety per cent of P demand is for growing food (Cordell et al., 2009). This demonstrates its key role for ensuring global food security. In addition, the main source of P, phosphate rock reserves, is finite on a human time scale (ibid.). Despite this knowledge, P is currently not managed sustainably. This is of alarming concern - especially since it cannot be substituted by any other element. The factors attributing to P concerns on a global level are shortly addressed below (A more extensive explanation of the issues surrounding P, its chemical properties and pathway is given in Chapter 4).

One of the main P challenge is the global dependence on *inorganic* fertiliser, for which phosphate ores are being mined. Whilst soil can also be kept fertile by adding *organic* sources of P (containing carbon), such as animal manure or compost, various authors state that current levels of food production would not be maintained without the availability of this inorganic fertiliser (Cordell et al., 2009; Schröder et al., 2010; Van Vuuren et al., 2010). This dependency is a cause of concern for several reasons. First, there is cause for geopolitical concern. Recent data shows that close to 75 % of the phosphate rock reserves - which are currently considered economically extractable for the mining of P - are located in Morocco and Western Sahara territories (USGS, 2013). This gives a single country much power over an important resource. Second, phosphate rock reserves are a finite resource as mentioned earlier. It is widely acknowledged that P mined from phosphate rock is becoming scarcer and increasingly difficult to access, causing a rise in costs for the exploitation of the remaining reserves. Scholz and Wellmer (2013) therefore state that a complex challenge is ahead in which price spikes need to be mitigated for farmers to ensure that the economic scarcity of P does not affect food security. A third issue is contamination. The phosphate ores, from which P is mined in order to produce mineral fertiliser, also contain cadmium and uranium. Consequently, the produced mineral fertilisers sold on the market often contain a slight percentage of these hazardous constituents, since complete removal is usually considered too expensive. As a result, soils, groundwater and eventually food become contaminated, deteriorating its overall quality (Keyzer, 2010; Schröder et al., 2010).

[1] Besides the presence of phosphorus in agricultural fertilisers, it is also added to animal feed for ensuring sufficient growth of livestock. It is found in detergents and even in beverages such as Coca Cola – serving as food additives for acidification (Emsley, 2000; Jasinski, 2004). A far more alarming example, is its use in creating nuclear weapons (Emsley, 2000).

Simultaneous to these developments, there is a growing demand for P. This can be attributed to a growing world population in need of more food and hence, fertiliser. An increase in demand is also due to emerging economies such as China and India, where prosperity is accompanied by dietary changes towards more meat and dairy products that are more P-intensive (Schmid Neset et al., 2008).

Despite scarcity and growing demand, there are losses of P taking place throughout the entire supply chain; during mining and processing, transportation, application on the fields, food production and consumption and waste treatment. These losses can have detrimental environmental effects. This occurs if too much P is discharged to surface waters, causing a phenomenon known as eutrophication[2], which can result in algae blooms. Such discharge can happen through excessive application of fertilisers which leads to leaching and run-off into ground- and surface waters (Smit et al., 2010) Another contributor to this issue is insufficient removal of P at wastewater treatment plants (WWTP) – or no removal at all, due to the absence of a WWTP. With partially, or even completely untreated wastewater (WW) being discharged to surface waters, environmentally harmful accumulation of nutrients occurs (Gücker et al., 2006). According to Rosmarin (2004), around 25 per cent of all P mined since 1950 has ended up in water bodies or in a landfill. This finally brings us to an interesting paradox and a unique problem of P: on the one hand there is an increased scarcity of P and on the other hand there is a harmful excess of P in water bodies (Cordell et al., 2009; Elser and Bennett, 2011). This clearly underlines the need for a more sustainable use of this resource by balancing its use in time and space.

1.2. Definition of research gap

P losses[3] take place in both rural and urban areas. Much research on P flows has focused on losses and potential solutions in the agricultural sector (Cordell et al., 2012) and Kalmykova et al. (2012) stress that urban areas can be marginalised due to the magnitude of agricultural P flows. Only a third of mined P is estimated to even reach urban areas (Cordell et al., 2009). Cities however form a key step in the flow of P within the global food system. They concentrate the demand for food and thus for P. Consequently, cities are highly dependent on a continuous supply of P and accordingly vulnerable to potential shortages in the supply chain of this resource (Hodson and Marvin, 2009). On the other hand, cities also concentrate the production of P-rich waste, particularly through human waste (urine and faeces) as well as organic (food) waste. As the world becomes more urbanised, with at least 9.6 billion people being estimated to live in urban areas by 2050 (United Nations, 2013) and the food production and consumption chain becoming increasingly concentrated in and around these urban centres, cities are - and will continue to be - evolving into P 'hotspots' (Cordell et al., 2009; Schmid Neset et al., 2008). Hence, there is significant potential for cities to recycle their phosphate-containing waste and thereby contribute to (urban) food security by decreasing the dependence on mined phosphate and associated price fluctuations and contaminations. As stated by Cordell et al. (2009), human urine for instance could provide more than half of the P that is needed for the fertilisation of cereal crops. In another study about the P flow through the Twin Cities

[2] For more information on this phenomenon, please read Smith et al. (1999)

[3] For a definition of 'loss' in this thesis see section 1.3

Watershed[4], Baker (2011) shows that if P is recycled and deliberately exported to surrounding farmlands, it would be sufficient to support around half of the supply for the metropolitan area.

Cordell et al. (2011) stress the complexity of P management, which arises from multiple inter-linkages with other resources (e.g. nitrogen, carbon, land, water) and requires taking other global environmental and social challenges into consideration. These include climate change, fossil fuel energy scarcity, water scarcity, land-use changes, population growth, urbanisation trends as well as eutrophication. Accordingly, future trends and drivers within food, sanitation, water, energy and environmental management sectors will influence the feasibility of establishing P reuse and recycling systems and make it necessary to seek for synergies. In cities, these sectors "interact with the very highest density of intersections and inextricable interdependencies" (Beck and Villarroel Walker, 2013). In addition, cities are hubs of knowledge and innovation. Hence, they play a crucial role in finding and implementing synergies between the described sectors[5]. Moreover, urban areas are the key to real action for implementation of solutions. When taking a global perspective on the above-mentioned challenges, urban areas might seem marginal. It is, however, just as important to consider local variability and differences between various levels that accrue from different ecological and social contexts (Metson, 2013). P flows in cities can differ significantly from flows on a regional or national level, especially in more developed countries, where agriculture is often more disconnected from cities. For instance, Kalmykova et al. (2012) show that the amount of P in the municipal solid waste (MSW) fraction can be much higher than estimated – for the case of Gothenburg in Sweden, it accounts for some 40% of the total amount of P flowing through the city. In contrast, studies on a global scale rather suggest that the vast majority of P, namely 75% to 90%, in urban areas is contained in sewage sludge. The authors therefore argue that the current nutrient management strategies of the municipality of Gothenburg that have so far focused on the recovery of P from sewage sludge, have to be revised accordingly in order to consider the stream of P in organic waste as well.

For urban, regional or national P management strategies to be effective, it is therefore important to take the differences between urban, regional, national, and global P flows into consideration and thereby better understand the specificities, role contribution and management opportunities of cities.

Acknowledging this need, the interdisciplinary thesis project that this study is part of, intends to explore the limitations and opportunities to foster P reuse and recycling[6] in urban areas. This joint project, which has been carried out by Timo Eckhardt and me, is based on the notion that exploring these limitations and opportunities requires a careful analysis of both the technological and social aspects connected to the urban transition towards sustainable P use. Bulkeley and Betsill (2005: 42f.) point out that "most analyses of urban sustainability attempt to document the extent to which cities are, or are not, becoming more sustainable through the use of indicators, flows, foot-prints and so on, and the practical challenges which are being encountered in putting the sustainable cities

[4] The Twin Cities Watershed encompasses most of the Minneapolis-Saint Paul metropolitan region in the US
[5] Benjamin Barber, an American political theorist, also emphasises the potential for cities to play a vital role in tackling the global challenges at hand and thus argues more decision power ought to be handed over to decentralised local governments. In his TED talk on June, 2013, he argues why mayors should rule the world. For more information see: http://www.ted.com/talks/benjamin_barber_why_mayors_should_rule_the_world
[6] For a definition of P reuse, recycling or loss see section 1.3

agenda in place.” While studies with such a focus were undoubtedly important, “such work has tended to reduce the analysis of sustainable urban development to a technical matter of institutional restructuring, traffic management, architectural design and the development of green technologies” (Whitehead 2003, p. 1187 in Bulkeley and Betsill, 2005; Cordell et al., 2013). In their report on urban resource flows and the governance of infrastructure transitions, Hodson et al. (2012) stress that the role of cities in systemically reshaping resource flows and the organisation of infrastructure are generally not well understood. This is largely due to the insufficient attention that has been given to “the fact that the design, construction, and operation of infrastructures […] create a socio-technical environment that plays an important role in shaping, and potentially reshaping, how resources are procured, used, and disposed of by the city” (Hodson et al., 2012: 791). Accordingly, they argue that determining the limits and opportunities for re-shaping resource flows in cities requires an understanding of the current state of material flows and the technical and social organisation of infrastructures as well as an assessment of the existing or potential socio-technical capability to shape resource flows. This notion is supported by Broto et al. (2012), who stress that little attention is paid to integrate social and political drivers that influence resource flows, whilst there is a need for understanding of stakeholders and agents involved.

To cover the technological and infrastructural aspects of P reuse and recycling in urban areas, a Substance Flow Analysis (SFA) was conducted in order to track the flow of P through an urban system, using the city of Wageningen in the Netherlands as an example case study. In addition, the infrastructural features of the waste management system were examined, since the infrastructure plays a key role in shaping the P flow towards reuse and recycling. The focus of the SFA is limited to P found in food related flows only. This is first and foremost due to time constraints that prevent assessing every flow in an urban area that contains P. Secondly, previous studies on P have shown that the flow of food contains the highest amount of P (Cordell et al., 2012; Kalmykova et al., 2012; Kirsimaa and van Dijk, 2013). Finally, much of the issues concerning P are related to the food system[7]. Based on the results of the baseline analysis, the feasibility of a number of alternative strategies on the level of infrastructure from the perspective of the municipality was investigated. Thereafter, the potential impact of these alternatives in increasing P reuse and recycling within the urban area was estimated.

Analysing the material side of P flows brings us only half way. As Mol and Dieu (2006) point out, these kinds of analyses do not provide insights, understanding and strategies on how to successfully and sustainably govern these resources flows. They “pay little or no attention to social systems and social networks themselves [such as the social interactions and dynamics, the power relations governing these material flows, or the non-material (money, information, etc.) flows that parallel these material and energy flows.” (ibid.: 304). Hence, a sociological contribution to the analysis of P flows that accounts for the above aspects is a necessary complement to the material flow analysis. Timo Eckhardt therefore addressed the social and governance aspects by analysing the network of stakeholders relevant for reuse and recycling of P flows in Wageningen, the Netherlands. For this a Social Network Analysis (SNA) was carried out, a technique that is capable of analysing this structure of social networks in a quantitative and systematic manner. The SNA methodology can uncover

[7] Eutrophication in water bodies through excess fertiliser and insufficient nutrient removal at WW treatment plants, potentially economic shortage of fertiliser for crop growing, etc. For more information see Chapter 4.

network structures that enable or constrain communication and collaborative processes between stakeholders towards more P reuse and recycling in Wageningen.

The specific case of the Netherlands was chosen, as its soils are on average highly saturated with P, which has led to severe eutrophication issues (Cordell et al., 2013; Smit et al., 2010). In addition, there is a high dependency on P imports in the form of fertiliser and animal feed (Smit et al., 2010). Although P flows on the national level are well researched, according to our knowledge and with the exception of Rotterdam (Kirsimaa and van Dijk, 2013) and Amsterdam (Reinhard et al., 2013), there have not been any analyses conducted of Dutch cities with regard to P flows. It is thus interesting to assess how the urban areas in the Netherlands relate to global and national P issues. The choice for Wageningen, a small city compared to Rotterdam (the latter being one of the largest cities in the Netherlands), was partly due to time constraints of this thesis project. Another reason for this decision was due to the importance of *also* considering the role and specificities of smaller urban areas. According to Hodson and Marvin (2009), it is the larger world cities that seem to be increasingly dominating in developing solutions to global issues such as climate change and resource constraints. The authors express the concern that it is the large metropolis areas that are defining the infrastructural and technological fixes to deal with these emerging issues. Fixes that would in turn be down-scaled to other cities in what they refer to as 'national urban hierarchies' (ibid.). These fixes are developed in specific world or large city contexts, yet might not be successfully replicable in other contexts that have different capabilities and opportunities (ibid.). Therefore, it is interesting to explore the urban specificities of a smaller Dutch city with regard to P flows. The emphasis of this joint thesis project is on the capacities and interests of the *municipality* of Wageningen to facilitate more P reuse and recycling.

1.3. Objectives and research questions

1.3.1. Objectives

Within the defined research gap and focus, the following main research objective was formulated:

To investigate urban infrastructural limitations and opportunities to enhance reuse and recycling of phosphorus food flows of Wageningen, the Netherlands.

This research objective was further operationalised into four sub-objectives:

- To identify the infrastructural features of the current waste management system that shape the phosphorus food flows of Wageningen, the Netherlands
- To examine the current performance on reuse and recycling of phosphorus food flows of Wageningen, the Netherlands
- To investigate the infrastructural alternatives that are feasible for the municipality to enhance the performance on reuse and recycling of phosphorus food flows of Wageningen, the Netherlands
- To estimate the impact of the identified alternatives on the performance of reuse and recycling of phosphorus food flows of Wageningen, the Netherlands

1.3.2. Research questions

The formulated research objectives were subsequently translated into the following main research question and sub-research questions:

What are urban infrastructural limitations and opportunities to enhance reuse and recycling of phosphorus food flows of Wageningen, the Netherlands?

1) What are the infrastructural features of the current waste management system that shape the phosphorus food flows of Wageningen, the Netherlands?
2) What is the current performance on reuse and recycling of phosphorus food flows of Wageningen, the Netherlands?
3) What infrastructural alternatives are feasible for the municipality that enhance the performance on reuse and recycling of phosphorus food flows of Wageningen, the Netherlands?
4) What is the impact of the identified alternatives on the performance of reuse and recycling of phosphorus food flows of Wageningen, the Netherlands?

For further definition and specification of concepts for this thesis, see Figure 1-1.

Definition and specification of concepts for this thesis

Infrastructure: concerns the physical infrastructure of the waste management system (wastewater and municipal solid waste) that determine whether P is reused, recycled, or 'lost'. P is lost when it cannot (with current technologies) return/be recaptured to re-enter the human food system. This loss can occur to the biosphere (water bodies) or within the anthroposphere (infrastructure and road works).

Reuse: The entire waste stream containing P undergoes a natural transformation process, in which P is maintained and the end-product can be used for human food production. Here, natural transformation is understood as a process of natural waste decomposition that does not require human intervention per se. It could however be an engineered and controlled process in practice. In this thesis only P reuse in the form of sludge produced through anaerobic digestion and compost from organic waste is applicable.

Recycling: P present in waste, where P is deliberately recovered and separated from other components in the waste (such as organic matter) to form a desired chemical formation. The end-product can be used for human food production. In this thesis only P recycling in the form of struvite precipitation is applicable

Performance: the P use efficiency with the fraction of P (in weight) reused or recycled of the total P input.

Feasible alternative: it is a known, proven technology (through previous pilots or projects), its implementation falls under the scope of influence of the municipality, and is within the (economic/organisational) limits of what the municipality can realise now and in the near future of five years.

Figure 1-1: Definition and specification of concepts.

1.4. Importance of research

The presence of a Nutrient Platform (NP) in the Netherlands since January 2011 (Nutrient Platform, 2014), and the recent formation of the European Sustainable Phosphorus Platform (ESPP) in March 2013 (European Sustainable Phosphorus Platform, 2014) for governing P on a higher level, clearly illustrates the need for a integrated P management approach has arrived on the political agenda. However, Dawson and Hilton (2011) rightfully point out that such proper evidence-based policy and planning can only be implemented, if P flows are accurately quantified - giving the necessary insight into potential priority sectors and appropriate actions. This quantification of P flows is required on a global, national, regional as well as local level (Dawson and Hilton, 2011; Kalmykova et al., 2012). Moreover, it is argued that P losses are more easily reduced in the urban arena, since it is humans that control the flow of the P-containing materials (products/waste) through cities (Dawson and Hilton, 2011). By investigating P flows of the city of Wageningen, the Netherlands, this thesis thus seeks to contribute to (i) the pressing need for quantification of P flows, and (ii) investigating what opportunities urban areas actually pose in achieving a closed loop practice of P.

1.5. Structure of report

The structure of this thesis is as follows: Chapter 2 explains the theoretical framework on which the research and analysis is based. Chapter 3 elaborates on the research approach, system boundaries and methods used to gather the necessary data. Chapter 4 provides depth and further understanding of the P challenges on a global and national level. Here also general background information is provided on P, its history and chemical properties. Chapter 5 introduces the chosen case-study: Wageningen, the Netherlands. Chapter 6 presents the results of the research. Thereafter, these findings are discussed in depth in Chapter 7. Finally, Chapter 8 presents the final conclusions and recommendations for further research as a result of this thesis.

2. Theoretical framework

2.1. Introduction

This chapter explains the background of the main method (Substance Flow Analysis) used in this thesis. First, the context in which this methodology originated is presented. Thereafter, the main methodology of Material Flow Analysis (MFA) is elaborated on of which Substance Flow Analysis (SFA) is a specific category. Finally, SFA itself is addressed.

2.2. Urban Metabolism

The concept of urban metabolism derives from ecology and is used to understand the interaction between humans and their surrounding environment. In 1883, Karl Marx initially posed the idea[8] of the metabolism in *Capital* and referred to this as the exchange between and the interdependent relationship of society and nature (Rapoport, 2011; Zhang, 2013).

With the "The Metabolism Of Cities" published in 1965, Abel Wolman was the first to apply the concept of metabolism to urban areas. More recently, researchers have started to advocate that urban areas need to resemble natural ecosystems. Natural ecosystems are understood as cyclical processes with high efficiency in its use of resources, while the urban metabolism is viewed as linear and wasteful. This notion has led Girardet (2008) to argue that sustainability of cities is only achieved if there is a shift from linear to a more circular metabolism. Rapoport (2011) mentions that this bio-physical approach that studies and quantifies material and energy flows is what most urban metabolism studies are focused on. This approach is connected to the field of industrial ecology that examines these flows to understand consumption, exchanges and transformations in industrial systems. The method commonly applied by industrial ecologists to track physical flows is referred to as MFA (Broto et al., 2012), which is further elaborated on below.

Overall, the concept of urban metabolism is thus vital for gaining insight into the way urban systems function, how resources are used, its efficiency and infrastructure characteristics, which is required in order to achieve sustainable resource management (UNEP, 2013).

2.3. Material Flow Analysis (MFA)

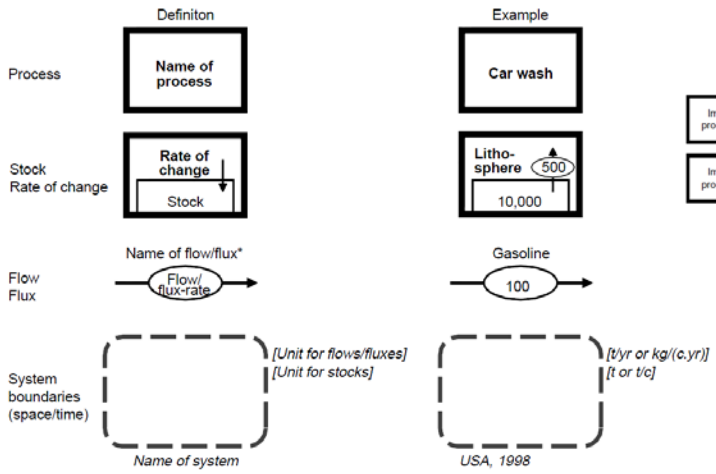
2.3.1. Introduction to MFA

The MFA concept is often described as a method that aims to understand the metabolism of the anthroposphere. As such, it analyses the relation and exchange taking place between ecology and society. The origins and use are in the field of industrial ecology, which takes its inspiration from nature and views the functioning of society as a metabolism. Industrial ecologists consider societal and industrial systems to be part of, and dependent upon, a larger biosphere. All of the resources required for the urban metabolism are extracted from the surroundings and are subsequently disposed of as waste in water bodies (hydrosphere), on soil (lithosphere) or are released into the air as emissions (atmosphere). Therefore, it is considered crucial to understand the current relationship and exchange that is taking place in order to develop a more sustainable system. By tracking all

[8] He gained this idea through a German soil chemist Justus von Liebig, who was concerned with the productivity of soil and lack of fertiliser. He proposed an urban-rural metabolism to ensure animal manure and human excreta were applied to enhance soil fertility (Rapoport, 2011). Ironically, these origins are still relevant today and connects with the phosphorus issues that we aim to address in this thesis.

material flows, identifying stocks (accumulations) in the system, MFA provides understanding and transparency (Baccini and Brunner, 2012; Bringezu and Moriguchi, 2002). Furthermore, it has the ability to point out the often linear nature of urban metabolisms, where resources are consumed and waste produced, thereby highlighting the urban vulnerability to shortages of resources (Broto et al., 2012).

MFA systematically assesses material flows and stocks through a system defined in space and time. Within this system, the network of processes[9] through which the materials flow, is also identified. An example of the building blocks of MFA (see Figure 2-1) and an exemplary MFA system (see Figure 2-2) is presented below.



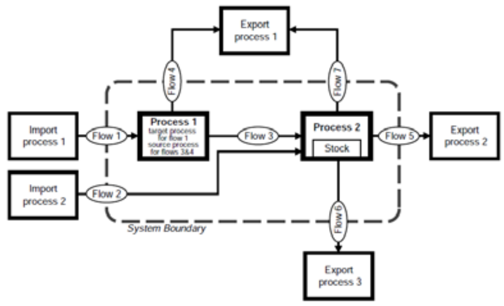


Figure 2-1. The building blocks of MFA: Good, Flow, Process, and System.Source: adopted from Brunner and Rechberger, 2004.

Figure 2-2. Exemplary MFA system illustrating selected terms. Source: adopted from Brunner and Rechberger, 2004.

A flow is always defined as a mass unit per time period such as tonne per year (Bringezu and Moriguchi, 2002; Huang et al., 2012; Kytzia, 2003). Material flow analysis is based on the law of mass conservation, which was discovered by Antoine Laurent Lavoisier (1743-1794). This dictates that everything going into the MFA system must be accounted for (mass balance principle), either through identified stocks, or outputs leaving the system (Baccini and Brunner, 2012; Broto et al., 2012; Huang et al., 2012). There is always a system boundary present that is defined in space and time. However, a virtual boundary (such as waste management system) is also possible (Baccini and Brunner, 2012).

According to De Haes and Heijungs (2009), the information obtained from MFA can be used to give insight into trends (accumulating stocks) and underlying causes of environmental problems. Thereby it has the capacity to identify present 'leaks' and inefficiencies in the system and can demonstrate what areas need attention in order to close the material cycle (Broto et al., 2012; de Haes and Heijungs, 2009). It can also give insight into certain pollution prevention policies through modelling the effects. Moreover, it is mentioned as a screening and visualisation tool that can identify further

[9] An example of this is for instance, paper (material) disposed of as waste by a company (process) 'flowing' to a waste treatment plant (process).

issues for investigation. Finally, it can be utilized as support for data acquisition. By systematically identifying the gaps of knowledge, it becomes clear which data still needs to be gathered (de Haes and Heijungs, 2009)

Hence, the main value of MFA resides in its potential to identify leaks, missing data and potential opportunities to fill these leaks. With the emphasis on environmental and health impact of materials, MFA has mostly become a governmental policy decision making tool (Bringezu and Moriguchi, 2002; Broto et al., 2012). According to De Haes and Heijungs (2009), from the 1980's onwards, it has become a common part of environmental statistical reports.

2.3.2. Various types of MFA

As material flow analysis is a tool for understanding the inter-linkages and dependency between the industrial and societal system and the larger biosphere, the insights provided can be used for achieving a more sustainable urban metabolism. This is usually guided by two objectives: (i) the detoxification or (ii) dematerialization of the industrial metabolism (Bringezu and Moriguchi, 2002). An important stimulus for pursuing these objectives have been publications such as ' The Limits to Growth' (Meadows et al., 1972) and Rachel Carson's 'Silent Spring' (1962).

When the focus is on detoxification, it is focused on the mitigation and/or substitution of critical substances, such as toxic heavy metals like lead and cadmium, that once released, cause detrimental environmental effects. General examples of environmental effects linked to specific substances are global warming ($CO^{2,}$, CH_4) or eutrophication (P) (Bartelmus, 2001; Bringezu and Moriguchi, 2002). The notion of dematerialisation is based on the recognition that resources are scarce and the current exchange (depletion and waste disposal) between the economy and the environment affects the ability of the industrial and societal system to function. Important concepts that relate to dematerialisation originate from Ernst-Ulrich von Weizsäcker et al. (1997) and Friedrich Schmidt-Bleek that proposed the factor 4 and factor 10 concept respectively (Bartelmus, 2001; Bringezu and Moriguchi, 2002; Hennicke, 2003). These factors refer to the amount of dematerialisation needed whilst at the same time enhancing the resource efficiency to achieve sustainability. Pursuing dematerialisation implies a reduced throughput of materials flowing through the economy or can more specifically address the amount of primary inputs or disposal of waste; thereby aiming at minimised environmental impact. These factor 4/10 concepts that stimulate eco-efficiency, have been adopted by the OECD and EU in the late nineties (Hennicke, 2003).

There are various methodological approaches within MFA that are dependent on the objective of the study. In Table 2-1, derived from Bringezu et al. (2009), the various types of MFA are addressed that focus more on detoxification (Type I), or on dematerialisation (Type II). Type I studies are driven by a focus on a certain substance or good. Type II focus on the throughput of material within entities such as firms, sectors, regions with the aim of evaluating their environmental performance which is more defined by their material intensive use and efficiency (ibid.).

Objects of primary interest	Specific environmental problems related to impacts per unit of flow of . . .			Problems of environmental concern related to throughput of . . .		
	Substances	**Materials**	**Products**	**Firms**	**Sectors**	**Regions**
	e.g. Cd, Cl, Pb, Zn, Hg, N, P, C, CO_2, CFC	e.g. wooden products, energy carriers, excavation, biomass, plastics	e.g. diapers, batteries, cars	e.g. single plants, medium and big companies	e.g. production sectors, chemical industry, construction	e.g. total or main throughput, mass flow balance, total material requirement
	. . . within certain firms, sectors, regions			. . . associated with substances, materials, products		
Type of analysis	**Ia Substance flow analysis**	**Ib Material system analysis**	**Ic Life-cycle analysis and assess-ment**	**IIa Business-level material flow analysis**	**IIb Input–output analysis**	**IIc Economy-wide material flow analysis**
Type of measure-ment tool	**Substance flow accounts**	**Individual material flow accounts**	**Life-cycle inven-tories**	**Business material flow accounts**	**Physical input–output tables/ NAMEA-type approaches**	**Economy-wide material flow accounts**
→ *Increasing importance for dematerialisation*						
Increasing importance for detoxification ←						

Table 2-1. Overview of various types of MFA. Source: adopted from Bringezu et al., 2009, table 2.1.

Type Ia

Substance flow analysis (SFA) is often used when there is a critical substance of concern that can potentially cause adverse health effects and pollution. SFA is thus clearly associated with the objective of detoxification. It is used to determine where the substance is released into the environment and to assess the associated impacts of this release. The spatiotemporal aspect is very important in SFA studies to understand what happens with a substance (how much of it is accumulated over time and where?). SFA's often serve as a baseline for further risk analysis (Bringezu and Moriguchi, 2002; Bringezu et al., 2009; de Haes and Heijungs, 2009).

Type Ib

Material systems analysis is often performed to understand bulk material flows that are investigated from the point of mining to disposal. It mostly concerns basic materials for human consumption, such as wood or metals and assesses the environmental impact that is coupled with its extraction and processing (Bringezu and Moriguchi, 2002; Bringezu et al., 2009). Bringezu and Moriguchi (2002) provide the example of aluminium, which is a material widely used, yet its production produces the toxic 'red mud' and is energy intensive.

Type Ic

Life Cycle Assessment (LCA) is a widely acknowledged and fairly standardised tool aimed at investigating the entire life cycle of a product. It is a very detailed and time intensive study, as all materials contained in the product are considered, together with the associated environmental impact per process stage. This cradle to grave approach is a system level and holistic perspective on what it takes to produce a product or service. As can be noted, a LCA study has a higher level of complexity when compared with an SFA (Bringezu and Moriguchi, 2002; Bringezu et al., 2009). Other forms of MFA can serve as a starting point or support for conducting an LCA (Huang et al., 2012).

Type IIa

Here, the main interest is the performance of a more localised entity such as a household or firm. The starting point is not a concern over a certain substance or good, but it is aimed at understanding and evaluating the throughput of materials to identify problems or enhance efficiency. According to Bringezu and Moriguchi (2002), this type of analysis is often used in companies for assessing their eco-efficiency and finding optimisation opportunities. Subsequently, it provides a basis for environmental reporting and performance assessment of a business. Yet, compared to LCA studies, this approach has a limited scope and not a chain perspective. As such, it cannot give a truly comprehensive overview of the environmental performance (Bringezu and Moriguchi, 2002; Bringezu et al., 2009).

Type IIb

With this type of analysis, industrial sectors are frequently investigated and the MFA methodology is applied to understand critical flows of interest within these sectors (CO_2 emissions are mentioned as an example by Bringezu and Moriguchi (2002)). Based on the inputs and outputs accounting, various industrial sectors can be compared with each other to make statements and draw conclusions about their environmental performance. Furthermore, in these studies, the identified environmental pressures can be combined with the monetary input-output of a certain sector.

Type IIc

Economy wide material flow analyses (or accounting) are frequently applied to analyse the metabolism of cities, regions, national and even international economies. Especially the economy wide MFA on a national scale has received much attention. Economy wide MFA is focused on studying the throughput of materials (its quantity and quality) through the area of interest and to assess the level of sustainability. This level of sustainability is defined rather through the objective of dematerialisation, since it aims at understanding the material intensity of the economy (how much is used). The various process stages within the economy are often not considered or shown, but only a total overview of the economy is given. This type of analysis has been standardised through guidelines provided by Eurostat and OECD, which illustrates that it is commonly used (Bringezu and Moriguchi, 2002; Bringezu, 2002).

As becomes apparent from Table 2-1 and the explanation, material flow analysis can take on various forms. Depending on the objective of the study, MFA studies can contribute to the formulation of policies (with regard to certain substances or measures that stimulate a higher efficiency of material use). Through its rigorous accounting method by adhering to the mass balance principle, it delivers valuable statistical information and data to understand bottlenecks and opportunities within the system. Furthermore, it allows governments and companies to set targets and devise standards for compliance and benchmarking - with the overall goal of sustainable exchange between the economy and the environment.

2.3.3. Substance Flow Analysis (SFA)

For this thesis, Substance Flow Analysis (SFA) is considered to be most suited, as it is concerned with one critical substance: phosphorus (P). The objective of this study goes beyond mere detoxification, as it is focused on a better stewardship and handling of the resource instead of eliminating or minimising its use. According to Cordell et al. (2012), SFA is a fundamental tool for improved P management by identifying key flows or hotspots. This in turn, facilitates more effective and targeted management of P. An overview of previous SFA studies on P can be found in Cordell et al. (ibid.).

Van der Voet (2002) has formulated a procedure for constructing a substance flow analysis and mentions the following three steps:

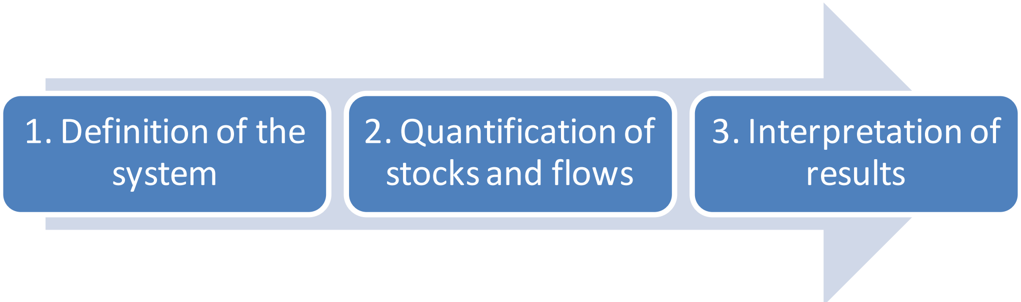


Figure 2-3: Steps in constructing an SFA. Source: figure based on van der Voet, 2002.

All steps require decisions to be made and are dependent on the objective of the study. The definition of the system requires a spatial demarcation, i.e. what scales are involved, what are the system boundaries and relevant processes to include. In addition, a functional demarcation is also required, that selects the goods and substances to which the study is restricted. Finally, the time unit of the study also needs to be considered and is usually a year (ibid.). The definition of the system and its boundaries for this study is addressed in detail in section 3.3.

The second step is quantification of stocks and flows. Here, several purposes can be distinguished. First, the substance flow analysis can be used for accounting, which is the most common MFA method. This entails keeping track of flows and stocks by registering them. This allows policy makers to analyse the current system for trends or to understand effects generated by policy that has been introduced and can also serve to identify missing or inaccurate data. A second option in quantification is static modelling (and steady-state modelling) where for instance the equilibrium state of a hypothetical management policy is calculated. It is explained to serve as a means to compare various management regimes. Thirdly, dynamic modelling can also be applied. This is suitable for building scenarios. Here, time information is necessary such as the retention time, life span of compounds etc. In this thesis, a combination of the first two approaches is chosen.

Accounting is important to gain an actual overview of the current state, whilst the static modelling lends itself for the hypothetical effect of formulated strategies.

The last step in the process is interpretation of the results, and here indicators perform an important function for the SFA to be useful for policy makers. Examples of such indicators are materials intensity, but also the leaks out of an economic cycle (ibid.). With regard to this thesis, the indicator to interpret the results is the relative amount of P from Wageningen that is reused or recycled of the total input (P use efficiency). This is referred to as performance of Wageningen.

3. Research approach and methodology

3.1. Introduction

This chapter outlines the methodology used to answer the aforementioned research questions. First, the research approach to answer the research questions is schematically presented. Thereafter, the general and more specific boundaries in which research questions were answered are addressed. Following that, methods of data collection and analysis applied for this thesis are outlined.

3.2. Research approach

Figure 3-1 presents a general schematic overview of the entire research process. To answer the research questions, both *quantitative and qualitative data* was required. To answer sub-question 2 and 4, an SFA was constructed (see Chapter 2) that requires quantitative information. More qualitative data was required to answer sub-question 1, and especially 3. To acquire all necessary data from the field, a *qualitative research approach* of personal communication and interviews was used, which was complemented by findings from literature (see section 3.4 for further explanation of methods used).

Essentially, the research conducted is twofold: the first two research questions concern the current 'baseline situation' and research question 3 and 4 concern 'alternative strategies'. It is important to note that the emphasis of this study is on mapping out the baseline, i.e. the current situation. Due to time constraints, it was not possible to perform an exhaustive research on possible alternative strategies.

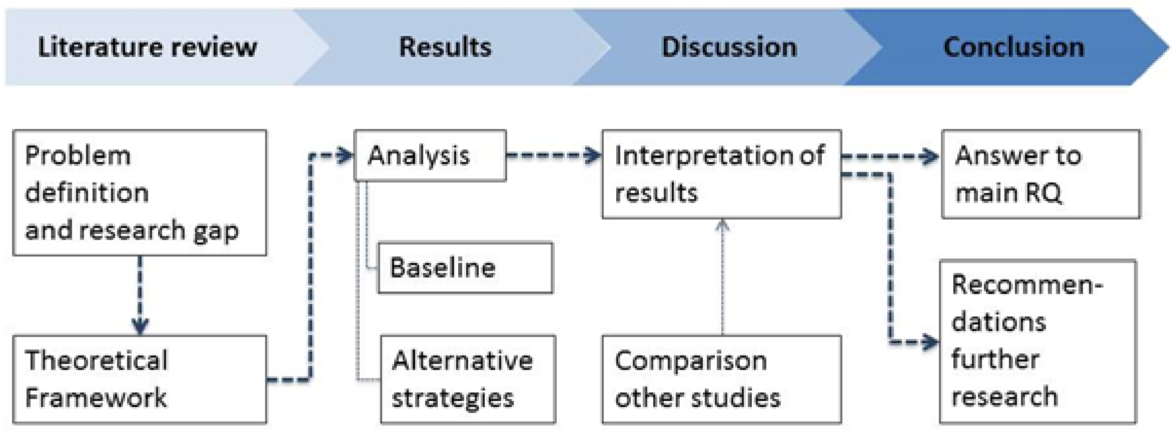


Figure 3-1: Research framework representing research process

3.3. System boundaries

As mentioned in section 1.2, the general system boundaries of this thesis is the city of Wageningen and the phosphorus (P) in food. This general focus requires further specification to understand how the research questions were operationalised and within what limits the research questions were answered. In the baseline, the limits of the case study are defined. Within these defined limits, research on alternative strategies is further delineated.

3.3.1. System boundaries baseline

The system boundaries with regard to research question 1: *'What are the infrastructural features of the current waste management system that shape the phosphorus food flows of Wageningen, the Netherlands?'* are as follows:

To better understand the possible pathways of P through the food system, descriptive research into the current waste management infrastructure was conducted. Here, 'current' is defined as the year 2012, since the sub question on infrastructural features provides the basis for answering research question 2, for which the base year of 2012 is used as well (see research question 2). The main delineation of this descriptive research on the waste management infrastructure is the city of Wageningen. However, the final destination of waste streams containing P are also mentioned (which are outside the borders of Wageningen), because the main interest of this thesis is to gain knowledge of the final destination of P in order to assess the performance (is it reused, recovered and recycled, or lost? For definition of these terms see 1.3).

The system boundaries with regard to research question 2: *'What is the current performance on reuse and recycling of phosphorus food flows of Wageningen'* are as follows:

To answer this research question, an SFA was conducted. According to Van der Voet (2002) the definition of an SFA system and its boundaries has several aspects, namely: the spatial demarcation, the functional demarcation and the time (and unit) demarcation.

Spatial demarcation

The spatial demarcation is mostly defined by the administrative borders of Wageningen. The scale is however not limited to the case-study site only. As explained with the previous research question, it is of interest to gain knowledge of the final destination of P. Within Wageningen, a division is made between households and non-households to assess the relative contribution of each sector to P reuse and recycling. A subsystem is created on the level of households to understand the internal distribution and division of P flows. Also for non-households, a further subdivision in scale is made into flows belonging to (i) the hospitality sector (which consists of restaurants, quick service restaurants (QSRs), pubs/cafés and hotels); (ii) business/offices (BO); (iii) Wageningen University and Research Centre (WUR)[10]; and (iv) supermarkets[11] to be able to provide a more nuanced perspective. Further subsectors that are relevant in an urban context with regard to P, are industry[12]

[10] WUR is separately addressed, because specific waste data could be obtained. Furthermore, WUR is one of the largest companies in Wageningen (Provincie Gelderland, 2013).

[11] Due to time constraints and lack of data, only food waste flows from supermarkets could be calculated instead of the entire retail sector (such as smaller shops selling food items).

[12] The exclusion of the subsector industry is due to several reasons. First, the only food-related industrial company is AgruniekRijnvallei; a company that produces animal feed. Although this flow certainly contains P, it is not directly consumed as food by humans and pets and is therefore outside the scope of this thesis (see functional demarcation and footnote on agricultural related activities). Another important reason for exclusion is that no actual data was supplied on waste flows and the average amount of P in the produced animal feed. The company itself saw insufficient relevance to supply such specific data (Marco de Mik, personal communication, February 18, 2014). Phosphorus is more discussed on a national level in cooperation with the entire agricultural sector including farmers and the national government (Marco de Mik, personal communication, November 8, 2013). Moreover, any losses taking place on the level of the industrial process (which might be relevant to capture when assessing the urban flow of P) are expected to be very minimal. Marco de Mik (personal communication, November 8, 2013) explains that AgruniekRijnvallei has a very efficient process and any losses of animal feed (and potentially P) happen at farm level, which is outside the system boundaries.

and agricultural related activities[13] (Kalmykova et al., 2012). Both of these subsectors are not considered in this study. Outside Wageningen, a division is made between the various destinations of P output (waste streams). Here, a subsystem is created for the wastewater treatment plant (WWTP), in order to gain a better insight into the internal distribution and pathway of P[14].

Functional demarcation

As explained in section 1.2, the functional demarcation of this thesis is limited to P present in food related flows, as this represents the most prevailing flow of P through an urban area. This includes all food consumed by humans and pets (ending up as excreta), and all food *not* consumed by humans and pets (ending up as waste). A lack of data and time hindered the tracking of *all* food flows in Wageningen. Therefore, the following limitations are applied: The food-related flows of P found in wastewater (WW) are comprised of human excreta, small amounts of pet excreta (aquarium fish) and food waste going down the drain. The latter category could only be calculated for households, since a lack of data prevented such explicit calculations for each subsector in the non-household sector. In addition, it is important to note that a lack of data resulted in numbers on WW from the non-household sector being aggregated and not defined (downscaled) for each subsector separately. P found in municipal solid waste (MSW), on the other hand, is separately estimated per subsector. For the calculation of P in MSW flows from BO, only waste from company catering was taken into account[15].

Time and unit demarcation

The time is demarcated by an annual flow, for which the base year of 2012 is chosen. This is due to the fact that one of the most important and reliable data obtained is from the water board 'Vallei en Veluwe'. This water board is among other responsible for the WW treatment of WW coming from Wageningen (van der Molen, 2012). The water board provided numbers on the P influent and effluent (in mg/L) of the concerned WWTP which are from 2012 (Waterschap Vallei en Veluwe, 2012). It proved difficult to find all data and sources from this base year. Therefore, some of the

[13] Within the administrative borders of a city there are often some agricultural activities to be found (including urban farming). In contrast to the national and global scale, the relative size and share of agricultural related phosphorus flows are found to be marginal on the urban level in comparison with phosphorus found in WW and MSW (Kalmykova et al., 2012). This is also expected to be the case within Wageningen, because there are few farmers and they are mostly focused on crop growing. The expected amount of P in the 'waste flow' arising from these few farming activities and the potential leaching and/or run-off is expected to very small and thus negligible (Bert Smit, personal communication, October 20, 2013). Moreover, any crop waste often remains on land or is composted and internally reused already (no P flow going in or out) – whether it concerns regular farming or urban farming (Klaas Nijhof, personal communication, November 7, 2013 and Gerard Derks, personal communication, November 15, 2013). This knowledge, in addition to time constraints, led to the focus of P found in WW and MSW, originating from households and the non-household sector.

[14] In the sub-system of the WW treatment plant no return flows are considered in the SFA. Although these streams are present (see section 6.2.1.1) and do contain P, it is not a yearly accumulating stock within the WW treatment process that needs to be accounted for.

[15] Calculations for company catering were based on a fairly thorough study by Van Westerhoven and Steenhuisen (2010) that investigated food waste flows originating from company catering in the Netherlands. Furthermore, it is expected that the largest fraction of food waste originates from company catering. Food brought from home and discarded at the workplace is assumed to be very small in comparison. Moreover, it proved fairly difficult to gather data on the total amount of food waste originating from businesses/offices (BO): All waste collection/processing companies that collect company waste, and that are active in Wageningen, were contacted. Many did not reply, and from the ones that did, it turned out that there is no detailed data reporting on the amount of organic waste and mixed waste collected in a city or region (Anja Spee, commercial employee at ACV group, personal communication, November 15, 2013, Maarten Duineveld, personal communication, November 29, 2013).

numbers used for calculation of other flows are from reports that are not from 2012. Overall, the most recent sources and/or closest to the year 2012 are used for the calculation of flows. The unit used for calculations in this thesis is tonne/year (t/yr).[16] This unit is most commonly applied in similar urban studies on P (such as the study by Kalmykova et al. (2012)) and makes eventual comparison easier.

3.3.2. System boundaries alternative strategies

The system boundaries with regard to research question 3: *'What infrastructural alternatives are feasible for the municipality that enhance the performance on reuse and recycling of phosphorus food flows of Wageningen, the Netherlands?'* are as follows:

Within the set boundaries of research questions 1 and 2, there is further demarcation with regard to infrastructural alternatives. The focus is limited to infrastructural alternatives that are within the scope of influence of the municipality of Wageningen. With regard to the WW system, this means alternatives are limited to alterations on the sewer system (which fall under responsibility of the municipality), or on WW collection of events where a permit from the municipality is required according to Wouter de Buck, secretary at the Nutrient Platform (NP) (personal communication, October 18, 2013). With regard to MSW, the alternatives only concern MSW collection systems for *household waste*, since the municipality is held responsible for the collection of this waste (Gemeente Wageningen, 2012a)[17]. This means any alternative collection infrastructure for MSW from the *non-household sector* is not considered. Within the non-household sector, the municipality does not have the same impact and decision power as with the centralised WW system that covers both household and non-households[18]. An additional reason for excluding the non-household sector is its diverse nature and simply a lack of data and time to research possible options and their feasibility. Moreover, the calculations made for the non-household sector are much less accurate and reliable compared to households (see section 7.5.2). The non-household sector is often confidential about its waste streams and the amount produced. This makes the basis on which to formulate alternative strategies too uncertain.

The research on infrastructural alternatives is limited to (pilot) projects that are taken place in the Netherlands with regard to WW and MSW, as it was not possible to research initiatives that have implemented in other parts of the world. Furthermore, the validity of the suggested alternatives is expected to be higher when taking case studies in the Netherlands compared to case-studies from abroad with different legislation, conditions etc. Finally, the final alternatives chosen are limited by current and future plans formulated by the main stakeholders involved in the waste management infrastructure (the municipality, the water boards and the MSW companies) to ensure its feasibility in the very near future and thus being low-hanging fruit (approximate time span of five years).

The system boundaries with regard to research question 4: '*What is the estimated impact of the identified alternatives on the performance of reuse and recycling of phosphorus food flows of*

[16] Please note that in the software STAN, which is used for constructing the SFA, the unit tonne/annum (t/a) is displayed. This could unfortunately not be altered.
[17] Although the municipality also has influence on which waste processors are contracted (Gemeente Wageningen, 2012a) the emphasis was not put on this matter. Especially since the current waste processor, Twence, is already ensuring a return of the nutrients (P reuse) back into the soil in the form of compost (Gemeente Wageningen, 2012a)
[18] The non-household sector can contract any waste collection and processing company for its waste streams. This decision is beyond influence of the municipality (see section 6.2.1.2).

Wageningen, the Netherlands?' are defined by the formulated alternatives in research question 3. The calculated impact of the alternatives strategies on the flows of P are only an estimation, since a lack of time and data prevented more precise and accurate calculations.

3.4. Methods of data collection

After defining the general research approach and the relevant system boundaries, the methods used to gather the relevant data are elaborated on. First, the general methods of data collection that were used to answer the research questions are addressed. Thereafter, the methods are schematically represented per research question.

3.4.1. Literature search

A comprehensive literature review on P issues on a global, national (Netherlands) and urban level, was conducted and co-written together with my thesis colleague Timo Eckhardt. This served as a starting point for identifying the research gap and formulating research objectives and questions for this thesis. Furthermore, it served as a preparation for the joint thesis project, to gain a better understanding of the context and the issues surrounding P. Subsequently, scientific literature was consulted for developing the theoretical framework. Scientific and so-called 'grey' literature - which is often defined as reports (institutional, governmental, company reports etc.) conference proceedings and doctoral theses (Farace and Schöpfel, 2010) - was also used to acquire necessary data to answer the formulated research questions.

3.4.2. In-depth interviews

In-depth interviews are an intensive qualitative research method that is often limited to a small number of respondents with the objective to explore perspectives on a particular topic (Boyce and Associate, 2006). This research method was chosen due to its open-ended, exploratory nature that allows for probing and discussion on issues and perspectives. This provides relevant background information and insights into the context and reasoning behind opportunities and limitations on advancing a closed loop practice regarding P. In-depth interviews are often conducted by using a certain set of guidelines. This is also known as semi-structured interviews (Flick, 2006; Guion et al., 2011). Semi-structured interviews are thus guided by a set of topics that frame the interview (plus a number of sub-questions). These topics were in most cases similar in all interviews, to ensure comparison between findings on certain subjects addressed. Yet, sufficient room was kept for an iterative process in which topics are altered due to findings from previous interviews, or adapted to suit the profile of the interviewee in question.

The interviews held were divided into two stages. The first stage, co-conducted with my thesis colleague Timo Eckhardt, served as an explorative basis to gather views on the challenges of P. In these interviews, the following broad topics were addressed: the importance of P and nutrients (and their recycling and reuse) within the activities of the interviewee's organisation; the (potential) role of cities and local/regional governance arrangements regarding P recycling and reuse, actors and stakeholders that are relevant for P recycling and reuse in cities in general and in Wageningen specifically; drivers and motivations as well as barriers and obstacles for the interviewee's organisation to (not) deal with this topic; the potentials for a match of supply and demand of reused and recycled P. See Appendix V: Example topic list for interview. Thereafter, a second and much shorter series of interviews was carried out. These interviews were much more directed at gaining insight into opportunities and limitations for alternative strategies. Here, the baseline situation and much of the P issues were already known, which allowed asking more specific and directed questions.

The in-depth interviews were mostly conducted in person, or by telephone (via Skype). Interviewees were selected on the basis of their direct connection to the P flow of Wageningen, or if they were considered experts with relevant knowledge that is complementary in answering the research questions. In total thirteen in-depth interviews were conducted, of which nine together with my thesis colleague Timo Eckhardt. The time-span of the interviews was between thirty minutes and two hours. For more information see Appendix IV: Interviews.

3.4.3. Personal communication

In addition to in-depth interviews and literature, other forms of personal communication were used in order to obtain (additional) quantitative or qualitative information. In total, and addition to the interviewees, thirty-two relevant actors were contacted to provide information through email, or by telephone.

3.4.4. Site visits

To further a better understanding of the final destination of waste streams and the associated P, site visits to the WWTP in the city of Renkum and the solid waste treatment plant in Hengelo (of household MSW) were also carried out.

3.4.5. Other sources of data

Finally, when information could not be obtained through literature, in-depth interviews or personal communication - supporting sources of data were used. Examples of this are relevant documentation received from interviewees (company data) or publicly available data (including websites, statistics etc.).

3.4.6. Data collection methods per research question

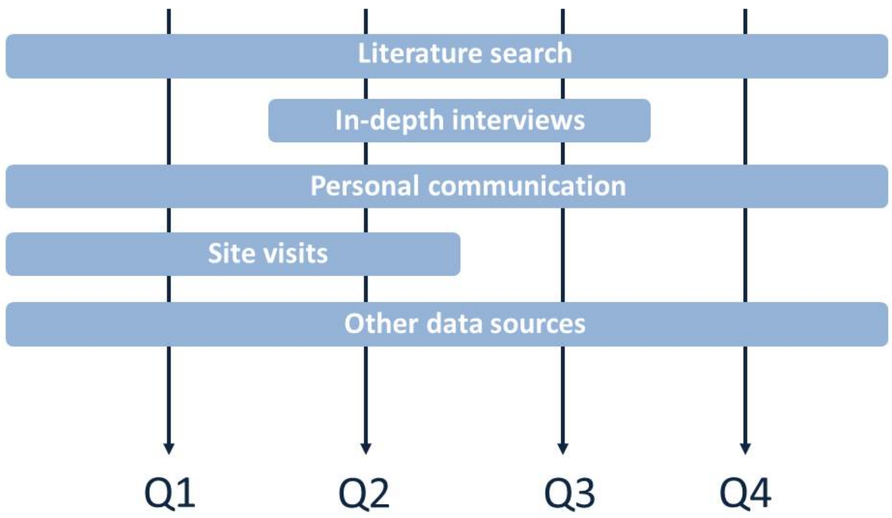


Figure 3-2: Methods of data collection, split per research question

3.5. Data preparation and analysis

3.5.1. Quantitative data

The quantitative data is gathered to answer research question 2 and 4. The response rate of people contacted to obtain quantitative information was 100 % in terms of interviewees and approximately 60 % in terms of other relevant actors. All quantitative data was first transferred to an excel sheet to maintain an overview and make calculations for each subsector and all connected P flows. Wherever possible, collected data was triangulated with other sources to ensure a higher validity. Moreover, the amount of P accounted for in waste streams was cross-validated with the P input, due to the mass balance principle of SFA (what comes in, must come out or retain as a stock).

All data was required to be 'prepared' by converting it into amount of P in t/yr in order to construct the SFA for analysis of the data. The acquired data on P *input* (domestic food supply of P to Wageningen), and output in the form of *excreta*, was already in a mass unit of P/time unit (excreta for instance is based on Dutch average dietary P intake, which was given in mg P/day). This meant that for these flows, only fairly simple mass and time conversions were necessary to calculate the amount of P in t/yr. With regard to P output in the form of *food waste* however, no exact amount of P was presented/known. In order to calculate the amount of P in t/yr present in food waste, it was necessary to (i) assess the amount of food waste per subsector, then (ii) assess the composition of food waste per subsector (iii), gather knowledge on the relative share of various food products (cheese for example) in the total amount of food waste, and finally (iv) gather knowledge of the amount of P of each food product (category).

After the collection and conversion of all necessary data, a computational analysis of the acquired knowledge was conducted by combining and inserting it into STAN (version 2.5)[19], which is a supporting software tool to construct an SFA (or an MFA). The format used in STAN is a sankey diagram, which means the thickness of the flows corresponds to their relative size. This illustrates the most important flows in one quick glance. There are several options for choosing SFA/MFA related software, of which an overview is found in Baccini and Brunner (Baccini and Brunner, 2012). For this report STAN has been chosen, since it is tailored to MFA/SFA methodology and easily accessible (free to download). Please note that in the software STAN, the unit tonne/annum (t/a) is displayed instead of t/yr. This could unfortunately not be altered.

As explained in section 2.3.3, the indicator to interpret the results, is the relative amount of P of the total input from Wageningen that is reused or recycled[20]. This is subsequently compared to previous urban SFA studies focusing on P.

3.5.2. Qualitative data

Of those people contacted for in-depth interviews, all were willing to cooperate. During the interviews, notes were taken which then served as a basis for a comprehensive minute of the interviews. In these minutes, views and comments were summarised and grouped per topic.

[19] For more information, see http://www.stan2web.net/.

[20] Reducing measures are outside the scope of this thesis. In the case of food, P always ends up in either MSW or in WW (in the form of excreta) where it needs to be converted to a useful product through reuse or recycling in order to close the loop. Whilst reducing food waste is also important to minimize the potential of P losses throughout the food chain, it is not the focus of this thesis.

Thereafter, the minutes were sent to the interviewees, who were asked to confirm and if necessary, add or correct information. When all interviews were conducted a thematic comparison was made, together with my colleague Timo Eckhardt, for comparison of interviews on the same topics (Meuser and Nagel, 1991)[21]. This last step allowed to identify general viewpoints, cross-validate, compare, or discover additional relevant topics.

[21] This process was inspired by the systematics for evaluating semi-structured interviews suggested by Meuser and Nagel (1991). It comprises the following six elements: 1. Transcription; 2. Paraphrase; 3. Headlines; 4. Thematic comparison; 5. Sociological conceptualization (empirical generalization) as well as 6. Theoretical generalization.

4. Context: The story of phosphorus

4.1. Introduction

In this chapter an overview is given of the 'story of phosphorus (P)'. Some aspects are already touched upon in the introduction, however this chapter elaborates on the issues more in depth. First, a general introduction explains the relevance of P as an essential nutrient, its chemical properties, and gives an overview of its pathway through the biosphere and anthropogenic system in specific. Thereafter, main issues concerning P on a global scale are examined, with a focus on the European Union considering the case study is based in the Netherlands. Subsequently, a closer look is taken at how these issues relate to the national level (the urban level is already addressed in section 1.2). Finally, a conclusion of the main findings is presented.

4.2. General introduction to phosphorus

4.2.1. History of phosphorus

The word phosphorus is derived from the ancient Greek words *phos*, which means 'light' and *phorus*, meaning 'bringing'[22] (Emsley, 2000; Föllmi, 1996) It is a chemical element referred to as P in the periodic table. As mentioned in the Introduction, P is an essential nutrient for all life on earth and cannot be substituted by any other element (Emsley, 2000; Föllmi, 1996; Schröder et al., 2010). It does not occur as a pure element in nature, but only as an oxidised form called phosphate, where the P atoms are surrounded by four oxygen atoms (PO_4^{3-}) (Emsley, 2000). Emsley (ibid.) explains that the term phosphorus and phosphate are often used interchangeably. As a matter of fact, it is correct to apply the term phosphate and not phosphorus. However, Emsley (ibid.) also mentions that it is common to refer to different phosphate forms found in nature under the collective title of phosphorus. For this thesis, the overarching term of phosphorus (mostly referred to as P) is used, yet sometimes specifically referred to as elemental phosphorus in this chapter when it concerns elemental P (existing as P_4, also known as white phosphorus, see below). Moreover, whenever relevant or necessary (to understand the chemical processes), the various phosphate forms will be distinguished by their chemical name. For a more comprehensive understanding of the properties of P, how it is produced and travels through the biosphere, see subchapter 4.2.2 and the chemical fact sheet in Table 4-1.

Phosphorus was the thirteenth element that could be isolated in pure form ibid.). The French chemist Antoine Lavoisier acknowledged P as an element in his Chemistry of Elements, published in 1789 (ibid.) It is suspected that Hennig Brandt, an alchemist in Hamburg, first produced elemental phosphorus in a pure form (white phosphorus[23]) in 1669 from heating urine in a furnace stoked with charcoal and called it phosphorus (Aldersey-Williams, 2011; Emsley, 2000; Föllmi, 1996; Sourkes, 1998). After this discovery, other alchemists and chemists also began trying to duplicate the process of creating elemental phosphorus and experimenting with the element once produced (Emsley, 2000). In 1769, urine was replaced by bones as the common material from which elemental

[22] Phosphorus is luminescent, which occurs as a result of an energy change within a substance. This is explained by the slow chemical reaction between phosphorus and the oxygen present in air. This happens on the surface of phosphorus, where a molecule formula of HPO is formed and an oxide of P_2O_2 (Emsley, 2000).

[23] In addition to white, red, Hittorf's and black phosphorus are also known. These are various structural forms of the same pure element (Emsley, 2000). White and red phosphorus are the most common and their difference is addressed in the chemical fact sheet as well as section 4.2.2.

phosphorus was extracted. In that year, Carl Scheele and Johan Gahn proved that bone consisted mostly of calcium phosphate (Aldersey-Williams, 2011; Föllmi, 1996). They found if bone ash was treated with sulphuric acid, it would release phosphoric acid. Heating this product with charcoal eventually produced elemental phosphorus (Emsley, 2000). The use of bone meal as a main source for the extraction of P was replaced by mineral phosphate rock (which contains calcium phosphate) in the 19th century, which was an even more abundant source of P (ibid.). Important for further development in the application of P were the chemist Robert Boyle and his apprentice Ambrose Godfrey Hanckwitz. By experimenting, they produced phosphoric acid and polyphosphoric acid (ibid.). These new forms were later to be used for fertiliser production and as food additives (see section 4.2.2).

Phosphorus also started to be used for medical treatment purposes in various doses and forms, as it was believed to cure all kinds of ailments. The use of P in medicine was boosted by the discovery of Professor Johann Thomas Hensing in 1719 that the brain tissue contained higher amounts of P than the rest of the body. This led him and many scientists with him to conclude that this element must have a profound impact on the workings of the brain and mental status (Emsley, 2000; Sourkes, 1998). However, elemental white phosphorus is highly toxic and a dose of only 100 mg for an adult is fatal (Emsley, 2000). Despite this dangerous property, white phosphorus was only removed from the British Pharmacopoeia, a list that describes all known medicaments, in 1932 (ibid.)

In addition to being toxic, white phosphorus is also extremely flammable (Aldersey-Williams, 2011; Emsley, 2000) and these properties led to white phosphorus becoming an important component of the match making industry. Due to the high flammability and toxicity, many accidents occurred. Eventually red phosphorus, another allotrope or structural form of elemental phosphorus, was discovered by Professor Anton von Schrötter in 1845, and was rendered much more safe and stable. This allowed the production of so called 'safety matches' (Emsley, 2000).

The flammable and toxic properties of white phosphorus were also soon to be used for warfare. Due to the introduction of the electric furnace in 1882, it became possible to produce white phosphorus on a larger and more efficient scale[24]. Subsequently, produced white phosphorus was used in WOI for smoke screens, tracer bullets and P bombs (Aldersey-Williams, 2011; Emsley, 2000). In WOII, P had taken even more lethal forms due to the experiments of German scientists. A potentially dangerous form of phosphates are organophosphates, in which carbon compounds are attached to the P molecule (Emsley, 2000). The German chemical company IG Farben began experimenting with organophosphates and investigated phosphorus-fluorine and phosphorus-cyanide compounds. Although it was initially in search of producing better pesticides, the outcome was the discovery of highly toxic nerve gases such as sarin (phosphorus-fluorine compound) and tabun (phosphorus-cyanide compound)[25]. These were manufactured in Germany during WWII and the company

[24] The production of white phosphorus in the UK went from 1,000 tonnes in 1914 to 2,500 tonnes in 1918.
[25] The workings of nerve gases are as follows: the body sends out messenger chemicals in the form of acetylcholine from the nervous system to activate the muscles. After activation, the acetylcholinesterase enzyme is necessary to split the chemical into acetyl and choline. Nerve gases bind themselves strongly to the enzyme and thereby preventing it to deactivate the acetylcholine. Without this enzyme, death quickly follows as there is a sort of accumulation of too much acetylcholine (Emsley, 2000)

produced a sufficient amount[26] that could have killed all human life on earth, yet fortunately, were never used (ibid.)

As mentioned earlier, these nerve gases were discovered in search of pesticides. Hence, organophosphates were also applied in the production of pesticides (Jasinski, 2004), albeit in different forms and lower doses[27]. A well-known organophosphate insecticide is glyphosate, patented in 1972 and produced by the American chemical company Monsanto (Emsley, 2000). This insecticide has been brought to the market in 1974 and is known as ´Roundup´ (Monsanto, 2014).

In addition to P being used for the production of pesticides to aid yield maximisation, P is also key component in fertiliser. Its importance for life was understood by scientists in the beginning of the 19th century, when they assessed the composition of plants and found that they also contain P. Justus von Liebig, a German chemist, stated in 1840 that fertility of the soil was influenced by chemical processes and argued for the use of P in fertiliser (Föllmi, 1996). Von Liebig analysed that plants need several components for growth: carbon dioxide, ammonia, water, potassium nitrate, calcium oxide (lime), magnesium oxide, iron, phosphorus, sulphate and silicate. While he did not manage to put together the ideal fertiliser, the farmer John Lawes and chemist Henry Gilbert did. On a plot in Rothamsted they discovered in 1837 that water soluble ammonium phosphates from bones gave very high yields. Through further experimenting, the exact ratio of sulphuric acid to bones was found, which kick-started the future chemical fertiliser industry (Emsley, 2000; Föllmi, 1996; Keyzer, 2010).

The application of P had also found its way through the food additives and detergent industry (Jasinski, 2004). For food additives, pure phosphoric acid is used directly or as a basis for producing suitable phosphate forms (Emsley, 2000)[28]. In detergents, it was found by the consumer goods company Procter & Gamble that the use of sodium trypolyphosphate (STPP) was highly beneficial, as it made the water softer and allowed the soap to perform better. As such it was introduced in detergents in 1946. However, in the 1970's this use was met with criticism, as the increased discharge of phosphate in waterways was found to pollute water bodies by causing eutrophication (this problem is still relevant today as described in subchapter 4.3.5) (ibid.).

Against this background, P has proven to be an element that has beneficial and very dangerous attributes. The chemical workings of P as well as its pathway through the biosphere are more explained in depth in the next subchapter: 4.2.2.

4.2.2. Understanding chemical properties of phosphorus, application and pathway

What makes P so essential to life? As already briefly explained in the Introduction; P constitutes an important element of our DNA and is thus an integral part of us as living beings (Ghosh and Bansal, 2003). Moreover, a cell requires adenosine triphosphate (ATP) to drive the chemical reactions that allow the cell to form its components and derive energy from glucose (Emsley, 2000; Föllmi, 1996).

[26] Only 1 mg is fatal (Emsley, 2000)

[27] Organophosphate pesticides basically have the same working as nerve gases, although they do not attach themselves that easily or that strongly to the enzyme acetylcholinesterase (Emsley, 2000).

[28] An example of direct use is the adding of phosphoric acid to Coca Cola drinks - giving a certain 'tang' to the taste. An indirect example is polyphosphates, which are produced by heating phosphoric acid, which are used in meat processing. It has water holding properties, making the meat tenderer. It also improves shelf life, as it binds with copper and iron, which are essential elements to spoilage bacteria (Emsley, 2000)

Outside the cells there are cyclic-adenosine monophosphates (cyclic-ADM) that transmit information throughout the body and allow the release of hormones (Emsley, 2000). We obtain the necessary daily amount of 700 mg of P through food (see Table 4-1). As also plants and animals require P for functioning and growth, our food security is very much linked to the availability of P. Therefore, it is crucial to understand our food chain and how P is passed through this chain to ensure proper management.

The food chain starts with the presence of P compounds in the soil for plants to uptake. There are three natural cycles that supply P compounds to the soil: (i) the inorganic cycle, (ii) the organic cycle that is water based and (iii) the organic cycle that is land based (Emsley, 2000). An illustration of these cycles is found Figure 4-1. According to Schröder et al. (2010) the biogeochemical cycle, or inorganic cycle of P consists of four steps: (a) P containing rock is exposed due to tectonic uplifts, (b) subsequently weathering releases it into the environment and (c) part of it is transported through rivers and lakes where (d) finally sedimentation takes place (Föllmi, 1996). The flows through this cycle can take up to millions of years. The water based cycle circulates the P compounds between the living creatures in rivers, lakes and seas. The land based cycle transfers P compounds from plants to animals that excrete them back onto the soil. Both land and water based cycles move much faster, from several weeks up to one year in the water and in the land based cycle, respectively (Emsley, 2000).

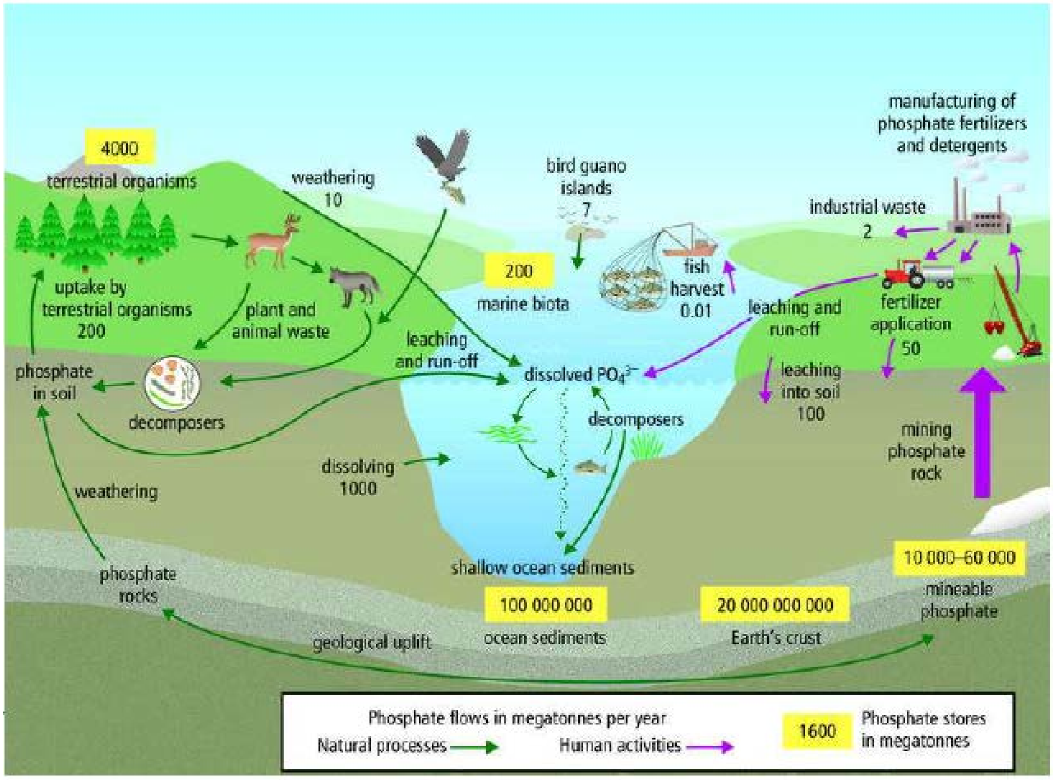


Figure 4-1: The phosphorus cycle. Source: Adopted from Van Dijk, 2013.

Although not explicitly depicted in Figure 4-1, a small fraction of P (some 4-5 % of total P mobilised on continents) can travel through air in the form of leaf and/or dust particles, spores and pollen (Föllmi, 1996). This is however due to wind and not caused by chemical transformation of the element towards a gaseous state. Overall, it can thus be stated that its movement is *mainly* restricted to the three cycles described above (Emsley, 2000). Accordingly, there are soils that are naturally low on P compounds and that can more easily become exhausted, as there is insufficient natural replenishment. Thereby making such soils less suited for agricultural practices. Furthermore, the replenishment provided needs to be a soluble form of phosphate to be available to plants for take up (bioavailability) (ibid.).[29] Hence, in order to be able to boost crop yields sufficiently, humans have introduced their own cycle for P replenishment in soils by adding fertiliser. As explained in the previous section, 4.2.1, the practice of chemical fertiliser started only in the 19th century, when the relation of plant nutrition and soil qualities was scientifically investigated. Before that time, farmers used crop rotation, having land lying fallow, or applying organic fertiliser that has a source of carbon in it, such as compost or animal and human excreta (ibid.).

For the production of chemical fertiliser, the starting point is a source of phosphate for which phosphate rock is mainly used today. As phosphate rock is also a source of calcium phosphate, a similar treatment applies as for bone meal or bone ashes. The main objective of the process is to produce phosphoric acid, a plant available form of phosphate that is soluble (Emsley, 2000). This is done in two ways: a dry and a wet process. In a dry process, the phosphate rock is heated in an electric furnace to produce white phosphorus and subsequently phosphoric acid. The basic chemistry for producing white phosphorus is by strongly heating a source of phosphate (for example urine) and adding a source of carbon to ensure the strong grip of the oxygen atoms is broken to form carbon monoxide (CO). If there is sand present (SiO_2), it will react with any metals present. For example in urine, there is sodium present (Na^+), which binds with sand to form sodium silicate (Na_2SiO_3). This process has remained the same with the use of phosphate rock. In the current process, coke is being used as a source of carbon, and sand is used to react with the calcium and metals naturally present in the ore (such as cadmium and uranium) to form a certain molten slag (ibid.). The basic conversion of phosphate rock to white phosphorus is shown below:

$$2Ca_3(PO_4)_2(s) + 6Sio_2(s) + 10C(s) \xrightarrow{1.500\ ^\circ C} P_4(g) + 6CaSiO_3(l) + 10CO(g)$$

The produced elemental phosphorus is slowly oxidised to form phosphorus pentoxide (P_2O_5).[30] This is immediately dissolved in water which results in the production of high quality, pure phosphoric acid (H_3PO_4). Producing this phosphoric acid of elemental white phosphorus is known as a very expensive process, and is therefore not commonly used in the fertiliser industry. However, it's pure qualities does make it safe and suitable for use as food additive (Emsley, 2000; Jasinski, 2004).

The second option of producing phosphoric acid for the fertiliser industry is through a wet process, which results in a less pure product. Here, the phosphate rock is dissolved in sulphuric acid which also produces phosphoric acid as explained in section 4.2.1 (Emsley, 2000). In this process,

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[29] Not all phosphorus compounds present in the soil can be up taken by plants. Plants require a soluble form of phosphorus (H_xPO4). The plant takes up dissolved phosphate through its roots from the soil water – although this contains only 1 % of the phosphate necessary for normal plant growth. In addition, the bioavailability of phosphate is made possible with the help of micro-organisms and enzymes that release phosphate from organic debris in a plant available form. Moreover, the roots of the plant itself can make surrounding soil slightly acidic to realise solubilisation (Emsley, 2000). If there are metals present in the soil such as iron and aluminium, they will bind with P, making it unavailable to plants. Especially, the bond with iron cannot be broken easily (ibid.).

[30] When the amount of P in a phosphate source is addressed, it is usually mentioned as P_2O_5, as this is the conventional standardised method – especially in agriculture. An example of this is found in a source from FAO (2014).

phosphogypsum is produced as a byproduct (Keyzer, 2010), which is further discussed in section 4.3.3. The basic chemistry for the wet process is shown below:

$$Ca_3(PO_4)_2(s) + 3H_2So_4(aq) \longrightarrow 3CaSO_4(s) + 2H_3PO_4(aq)$$

In addition to P compounds, phosphate ores always consist of different elements that are naturally geochemically associated with phosphate rock, such as uranium and cadmium (Schröder et al., 2010). The wet process does not remove these metals and as a result, the produced phosphoric acid has impurities and contains a fraction of cadmium and uranium (Emsley, 2000; Keyzer, 2010). It is however a cheaper form to produce phosphates suited for fertiliser. It is also possible to dissolve phosphate rock in phosphoric acid, which produces an even higher content of phosphoric acid afterwards. This version is called triple superphosphate (Emsley, 2000).

The products obtained from processing the phosphate rock are thus suited for various purposes, yet around 90 % of the P demand is related to food production (Cordell et al., 2009). This dependence again stresses the importance of P for food security. The main commodities produced from phosphate rock are fertilisers (74 %) and industrial phosphates (7 %) - of which animal feed and detergents are the most important (van Enk et al., 2012; Van Vuuren et al., 2010). The pathways of the three main commodities through the biosphere are discussed below.

Once produced, fertilisers are applied on agricultural land, where a part of the P is taken up by plants through its roots and with the help of microorganisms (Emsley, 2000). The remainder is accumulated in the soil or runs-off in surface waters. Crops grown for agricultural purposes are harvested for food production or end up as crop residue. Once harvested, it depends on the crop type how much P is removed from the soils. So called seed crops remove the most, as the seed stores phosphate as inositol hexaphosphate to facilitate growth when it germinates. For example, potatoes remove around 11 kg of P/ha and wheat only 7 kg of P/ha (ibid.). A substantial amount of crops grown (and potentially even harvested) end up as residue, accounting for a total of 258 M dry t/yr on average in the EU (Scarlat et al., 2010). These residues are used for biofuel, surface mulching, animal feed and bedding, mushroom cultivation, horticulture and industrial uses (Lal, 2005; Scarlat et al., 2010).

The harvested crops either end up as food waste, or are consumed by animals and humans that subsequently as adults excrete close to a 100% of P with urine (60-70%) and faeces (30 %) (Schröder et al., 2010). The food waste and excreta are either recycled back onto agricultural land or discharged in sewage where the P immediately reaches surface waters or is (partially) removed in wastewater treatment plants (WWTP). The liquid effluent of the treatment plant also ends up in surface waters (Cordell et al., 2009; Schröder et al., 2010). The sludge of WWTP in the EU is mostly recycled back to agriculture or incinerated[31] (Milieu Ltd et al., 2010).

[31] In the EU in 2010, of the 11,564,000 tonnes of dry solids originating from WWTP, 42 % was recycled back onto land, 27 % was incinerated, 14 % land filled and 16 % went to other destinations, such as processing for use as a biofuel (Milieu Ltd et al., 2010).

The P in animal feed is partly retained by the animal, but mostly excreted for adults[32] (Kissinger et al., 2005). Once excreted, the manure in the EU is recycled after treatment back onto the farm, destined for the manure market[33], or processed otherwise[34] (Schoumans et al., 2010a, 2010b)

In addition to food commodities, phosphates are also used in other commodities, of which detergents form an important group (Jasinski, 2004). Phosphates are used in detergents to deactivate calcium and magnesium that make the water 'hard'. Hard water does not allow the soap to be sufficiently activated, but instead forms an insoluble 'scum'. By making the water 'soft' with phosphates, the soap is more effective at cleaning (Emsley, 2000). The P in detergents is discharged to the sewer towards a WWTP.

Due to its apparent importance for food and other commodities it is essential that this resource is managed sustainably. However, there are several issues that affect the sustainable management of P: the dependence on mineral sources of P, scarcity, soil contamination, increase in demand, health risks and losses occurring throughout the cycle. In subchapter 4.3 these issues are discussed more in depth.

Chemical properties	
Chemical symbol	P
Element number in periodic table	15
Atomic weight	30.97
Melting point	44°C (white); 590°C (red, under pressure)
Boiling point	280°C (white); 417°C (red, sublimes)
Density	1.82 kg/L (white); 2.35 kg/L (red)
Main allotropes (structural forms of elemental P)	
White phosphorus	Also known as yellow phosphorus. It consists of clusters of 4 atoms in a pyramidal array (P_4). It is made with the reduction of phosphate with carbon. It
Red phosphorus	If white phosphorus is heated under pressure for several days around 300°C, it transforms to red phosphorus. It is a more safe (neither spontaneously flammable or poisonous) and stable form of phosphorus than white phosphorus.
Levels of P in humans	
Blood	345 mg/L
Bone	6.7-7.1 %
Average daily dietary intake	900-1900 mg
Recommended daily dietary intake	700 mg

Table 4-1: Phosphorus fact sheet. Source: numbers and information based on FAS, 2010, Emsley, 2000 and RIVM, 2011b.

[32] Kissinger et al. (2005) have conducted a study of cattle (yearlings) in six feedlots. It appeared that 16.9 % of the feed phosphorus was retained by the animal and the remaining nutrients excreted.
[33] At the manure market supply and demand are matched. The excess manure of one farm can be supplied to another farm in need of nutrients within the country or abroad (Schoumans et al., 2010a).
[34] Schoumans et al. (2010b) mention treatment processes (such as incineration and WWTP) for the purpose of P recovery for P industries (potential products obtained could be ash based P fertiliser).

4.3. Global phosphorus issues

4.3.1. Dependence on mineral sources of phosphorus

Before any large scale mining activities and extraction of phosphate rock, other (renewable) sources of P were used and applied on soils, such as compost, bone meal manure and human excreta. However, there were increases in famine and low soil fertility that could not sufficiently support conventional agricultural practices (Schröder et al., 2010). Furthermore, there were concerns by the economist Thomas Malthus, who theorised that the way human population increased (multiplying) could never match the current way food production increases (more land necessary devoted to farming). Eventually, there would not be enough land for all mouths to be fed. Increasing soil fertility and the yields that agricultural land delivered was considered to be an outcome (Emsley, 2000). With the introduction of chemical fertiliser in 19th century it was made possible to enhance soil fertility on a much larger scale. For this initially bones were used as did Lawes and Gilbert (explained in section 4.2.1), but also guano deposits,[35] and later on mined phosphate rock, which was to be the most abundant source of phosphate to be exploited for the production of inorganic fertiliser (Schröder et al., 2010; Van Vuuren et al., 2010). This development enabled high crop yields enabling a fast rise in population growth. This rise was further stimulated by the increasing awareness of hygiene and medical science in the 19th century (Keyzer, 2010). It is stated by various authors that current levels of food production would not be maintained without the availability of inorganic fertiliser (Cordell et al., 2009; Schröder et al., 2010; Van Vuuren et al., 2010). Moreover, where there has been a clear rise in the application on inorganic fertiliser, there has been a decline in the EU from the 1980's onwards in the use of alternative sources such as animal bones[36] and human excreta[37] due to health and pollution concerns (Lamprecht et al., 2011). This development leads to an even stronger dependence within the EU on the use of mineral fertiliser. For food production alone, this is estimated by Schröder et al. (2010) at an annual import of 1.2 Mt (million tonne) P.

As many commodities, of which food is the most important and prominent, depend on the supply of P, the location of the phosphate ore reserves is a source of geopolitical tensions. According to the U.S. Geological Survey (2013), reserves are considered supplies that are currently economically extractable and recent data shows that close to 75 % of these reserves are located in Morocco and Western Sahara territories (see Table 4-2). Currently, in addition to Morocco (including Western Sahara), the US and China are also large producers of phosphate rock (van Enk et al., 2012).

[35] So called guano deposits are found in the Pacific coastal regions and islands (Peru). These are accumulated bird droppings and are rich in nitrogen and phosphorus – both vital compounds for plant growth. Alexander von Humboldt studied its properties in 1802 and this resulted in the exportation of these deposits. Thereby becoming the first external source of fertiliser (Emsley, 2000; Keyzer, 2010). Guano deposits currently do not play an important role in the phosphate market and are therefore not further discussed in this thesis (van Enk et al., 2012).

[36] At the end of the 1980's and beginning of 1990's, the BSE crisis broke out in Europe. The BSE (bovine spongiform encephalopathy), also known as the 'mad cow disease' is a deadly brain disease that might be transferred to humans and potentially cause a variant called Creutzfeldt-Jakob disease. Due to these health concerns, the EU has banned the feeding of animal proteins (such as bone meal) to farmed animals. Eventually this resulted in a drop of BSE cases; in 2000 there were still thousands of incidents that dropped in 2010 to 44 (EFSA, 2012; Lamprecht et al., 2011).

[37] The EU Sewage Sludge Directive (86/278/EEC), formulated in 1986, is aimed at regulating the use of sewage sludge (containing human excreta) in order to prevent harmful effects on soil, plants, animals and humans and states that sludge needs to be treated before applied. Most member states have even adopted more stringent criteria, such as the Netherlands, in order to prevent any heavy metal or pathogen contamination. This has led several member states to stop the recycling of sludge to land – as did the Netherlands in 1995 (European Commission, 2013; Milieu Ltd et al., 2010).

The supply of phosphate rock for the world market is however mostly dependent on Morocco (Cordell et al., 2009). The U.S. requires it for its own agricultural production and until recently, China had put a high export tariff to secure P for its domestic markets at the expense of foreign competition (Schröder et al., 2010). However, such export tariffs on raw materials such as P were ruled against by the World Trade Organization (WTO) (2013). Although this has led China to implement the WTO decision in 2013 (ibid.), the case exemplifies that phosphate mining countries are increasingly recognising their geopolitical position and the need for ensuring domestic food security. These developments put Morocco in a very strong position which leads to geopolitical concerns.

4.3.2. Scarcity of phosphorus

Although there is a high dependence on the availability of concentrated phosphate rock, it is not an infinite resource. As such, various authors have addressed concerns on physical scarcity and there have been estimations of peak production around 2030 (Cordell et al., 2009) (see Figure 4-2).

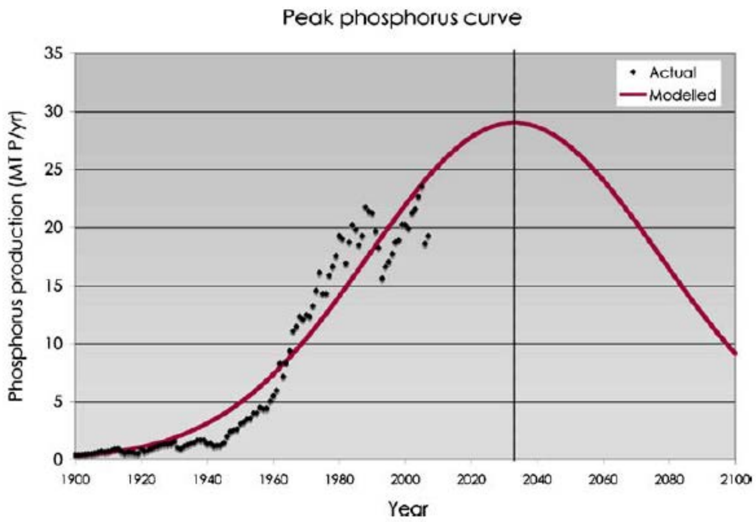

Figure 4-2: Prediction of peak phosphorus curve in MT (million tonne) P/yr. Source: adopted from Cordell et al., 2009.

However, it is stressed that there is a lot of uncertainty in the estimation data. Van Vuuren et al. (2010: 429) explain that this uncertainty "partly stems from the inherent uncertainty in estimating underground resources, with respect to (i) the likelihood of the discovery of additional resources, and (ii) technology development and production costs, determining what resources are realistically extractable at a given production cost". Moreover, it is argued that studies or models concerning P depletion are too simple and do not properly address the dynamics and uncertainty involved (Scholz and Wellmer, 2013; Schröder et al., 2010; Van Vuuren et al., 2010). Scholz and Wellmer (2013) therefore argue that predictions concerning physical scarcity in the near future are highly unlikely to occur. However, they do acknowledge potential economic scarcity, as the available reserves of P are determined by the economic costs involved. As Van Enk et al. (2012) explain, over 1600 deposits have been identified. However, only a fraction of these deposits are eligible for extraction. Based on the economic viability different categories are distinguished. The term 'reserve base' refers to those resources that are economic to extract (called reserves) marginally economic (marginal reserves) and sub-economic, which might be exploitable in the near future under certain price developments (sub-economic resources) (USGS, 2013; van Enk et al., 2012; Van Vuuren et al., 2010). This entails that the amount of what is considered 'reserves' may actually fluctuate. Technological developments that allow extraction under a certain cost or price changes in production instantly affect what is classified as 'reserves'. Such price changes are expected to come about if the ongoing depletion of easily accessible ores with a high concentration of phosphorus pentoxide (P_2O_5) continues (Cordell et al., 2009; Van Vuuren et al., 2010).

If prices increase, previously 'expensive' deposits may become more interesting to extract. For instance in Europe, that currently imports all P, there are known deposits of phosphatic chalk that have relatively low concentrations of P_2O_5 (in the range of 7 to 15 %), may become more interesting to extract if prices go up (van Enk et al., 2012). Although an increase in the price might stimulate the market to seek for other physical deposits to extract P, any rise in cost will undoubtedly affect the prices of food production and consumption. Scholz and Wellmer (2013) therefore state that a complex challenge is ahead in which such price spikes need to be mitigated for farmers to ensure the economic scarcity of P does not affect food security.

4.3.3. Pollution through phosphorus fertiliser production and consumption

Another pertinent issue is soil and groundwater contamination due to the use of mineral fertiliser. Thereby affecting food safety (Keyzer, 2010; van Enk et al., 2012). As mentioned in section 4.2.2, phosphate ores also consist of cadmium and uranium that pose concern due to their toxicity[38] and radioactivity[39] respectively (Schröder et al., 2010). During fertiliser production with the use of sulphuric acid, the by-product produced is phosphogypsum, which contains most of the heavy metals. According to Keyzer (2010), there is a production of 1.46 tonnes of phosphogypsum per tonne of phosphate rock processed. This hazardous by-product needs to be removed, and poses serious concern. Due to its radioactivity it often has to be landfilled, as other uses are considered too dangerous (ibid.). However, a slight percentage of these elements can be found in mineral fertilisers[40] as full removal of these heavy metals is usually considered too expensive. As a result, soils, groundwater and eventually food becomes contaminated, deteriorating its overall quality (Keyzer, 2010; Schröder et al., 2010).

There is concern that the quality of phosphate rock further declines if high grade ores are depleted. The lower grade ores have less concentration of P_2O_5 and higher concentrations of heavy metals (Schröder et al., 2010). This is expected to lead to price increases due to the need for further processing to remove these constituents (Keyzer, 2010; Maurer et al., 2006). The dependence on mineral fertiliser thus affects soil quality and thereby creates an important incentive to enhance recycling and recovery of other (organic) sources of P such as solid organic waste and manure.

[38] For more information on the cadmium content of phosphate rock reserves in mg/kg P, see Schröder et al. (2010), table 3.5.

[39] The ratio of uranium in deposits of phosphate rock are 3/22 (Keyzer, 2010).

[40] Keyzer (2010) states that N, P and K contained in a bag of fertiliser at best covers 60% of the total composition. When calcium, oxygen, hydrogen are also considered, then 98% of the total weight is accounted for. The remaining 2 % however, according to Keyzer, are likely heavy metals such as cadmium and uranium. Schröder et al. (2010) explain that, for instance cadmium, can be removed from fertiliser through calcination or co-crystallisation with calcium sulphate anhydrate. However, these are both very expensive processes.

4.3.4. Increase in phosphorus demand

Whilst there are concerns on economic scarcity and degrading quality of phosphate rock, simultaneously there is a growing demand for P due to several factors. First, the United Nations (UN) (2013) estimates the world population to grow over nine billion by the year 2050, which will result in an increased demand for food and thus fertiliser. It is estimated by U.S. Geological Survey (USGS) (2013) that the world consumption of fertilisers is going to increase from 41.9 Mt in 2012 to 45.3 Mt in 2016. The quantity of phosphate rock mined in 2011 and 2012 to serve the demand in general is shown in table 2 (ibid.).

	Mine production		Reserves[4]
	2011	2012[e]	
United States	28,100	29,200	1,400,000
Algeria	1,500	1,500	2,200,000
Australia	2,650	2,600	490,000
Brazil	6,200	6,300	270,000
Canada	900	900	2,000
China[5]	81,000	89,000	3,700,000
Egypt	3,500	3,000	100,000
India	1,250	1,260	6,100
Iraq	30	150	460,000
Israel	3,100	3,000	180,000
Jordan	6,500	6,500	1,500,000
Mexico	1,510	1,700	30,000
Morocco and Western Sahara	28,000	28,000	50,000,000
Peru	2,540	2,560	820,000
Russia	11,200	11,300	1,300,000
Saudi Arabia	1,000	1,700	750,000
Senegal	980	980	180,000
South Africa	2,500	2,500	1,500,000
Syria	3,100	2,500	1,800,000
Togo	730	865	60,000
Tunisia	5,000	6,000	100,000
Other countries	6,790	6,000	390,000
World total (rounded)	198,000	210,000	67,000,000

Table 4-2: Phosphate Rock. Statistics and Information. Data in thousand metric tonnes. Source: Adopted from USGS 2013.

Secondly, dietary changes towards meat and dairy products (related to increased prosperity in emerging economies such as China and India) that requires more P to produce. Another important stress on the demand of P is a rise in the use of biofuels and associated energy crops[41]. Due to growing environmental concerns regarding fossil fuels and meeting the energy needs for the future, biofuels are considered an interesting alternative (Cordell et al., 2009; McKendry, 2002; Schröder et al., 2010).

[41] Schröder et al. (2010) state that the biofuel demand will further increase the need for fertiliser. As the production of biofuels aims *not* to compete with agriculture, marginal land is used for growing energy crops. This is assumed to have a low fertility status and thus in need of phosphate fertiliser to be able to grow crops. It was estimated in 2007/2008 that the total need for growing biofuel crops was 0.34 Mt of P (ibid.).

4.3.5. Losses

Despite the economic scarcity issues and growing demand, there are losses of P taking place throughout the entire supply chain: during mining and processing[42], transport, application on the fields, food consumption and production and waste treatment. For food production, which represents the primary demand of phosphate rock, Cordell et al. (2009) give an overview of the losses at each stage (see Figure 4-3). Schröder et al. (2010) mention that prior to the industrial revolution and the introduction of mineral fertilisers, the connection between production and consumption of food was much closer in space and time and thus allowed for more closed loop practices. Following the introduction of mineral fertilisers, higher yields were achieved and there was no necessity for recycling the waste product anymore. In spite of increasing yields, Schröder et al. (ibid.) remark that it also led to a spatial segregation between production and consumption.

As previously stressed in the Introduction, losses can also cause harmful effects on the environment. When too much P is being discharged to surface waters, this contributes to the phenomenon known as eutrophication. Excessive application of fertiliser often contributes to this problem, leading to P saturated soils where P can more easily leach or run-off into ground- and surface waters (Smit et al., 2010). In addition, WWTPs also have a role and responsibility in removal of P from wastewater (WW) to avoid harmful accumulation of nutrients in water bodies. With the knowledge that much of the P ends up in landfill or water bodies (Rosmarin, 2004), whilst there is growing demand and fear for (economic) scarcity – the necessity to manage this valuable resource more sustainably becomes undeniable. The next section (4.3.6) will shortly discuss current efforts that are being undertaken to achieve this.

[42] For example, the beneficiation process (concentration) and cleaning process taking place in producing phosphoric acid, some of P is lost when contaminants such as iron phosphate are removed (Schröder et al., 2010) as iron binds strongly to P (Emsley, 2000).

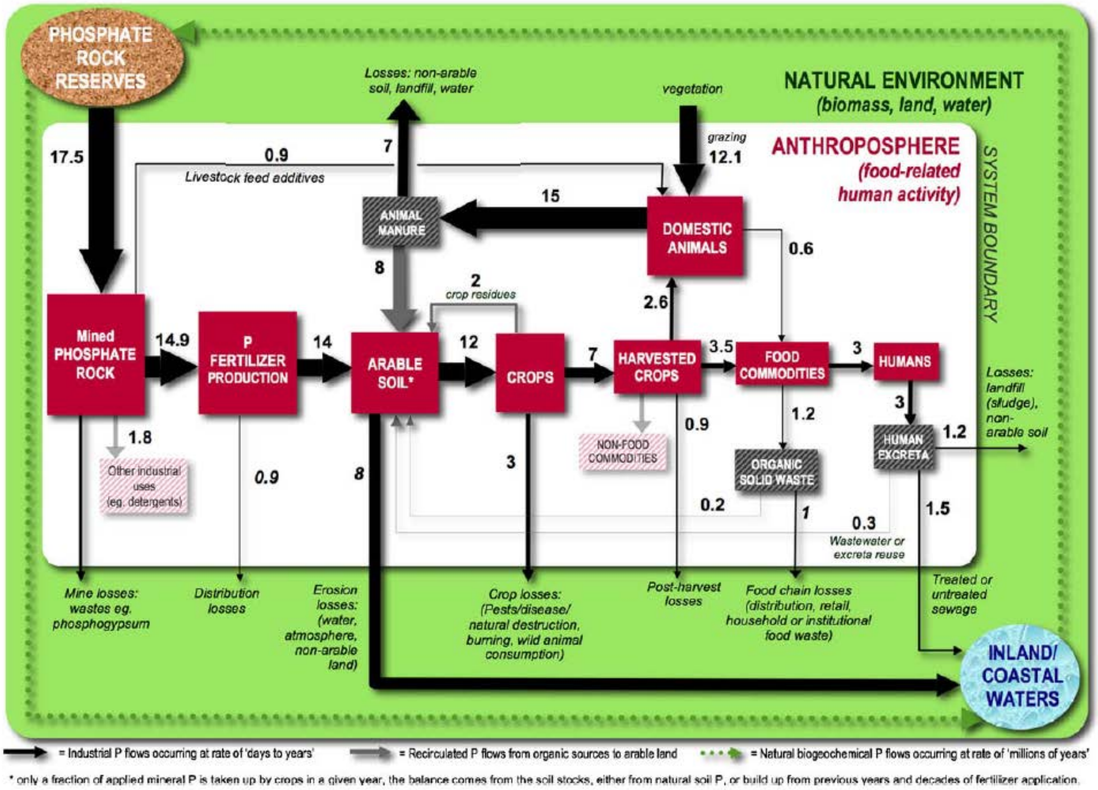

Figure 4-3: Key phosphorus flows through the global food production and consumption system, indicating phosphorus usage, losses and recovery at each key stage of the process. Units are in Million tonnes per year (Only significant flows are shown here, relevant to modern food production and consumption systems). Source: Adopted from Cordell et al. 2009.

4.3.6. Possibilities for more sustainable phosphorus use

There have been efforts and initiatives for recycling and recovery of P from waste streams. Recycling takes place in the form of manure and WW effluent being put on agricultural land as well as compost originating from solid organic waste. A disadvantage of organic waste, is that the solubility and bio-availability is not always clear and defined (Rittmann et al., 2011). Schröder et al. (2010) also mention that it is challenging to match waste streams with application in agriculture. Not only the bio-availability to plants is important, also the quality needs to be sufficient without any trace elements of potential heavy metals. Hence, if the product is to be used as commercial fertiliser, the solubility and the quality of the product need to be more clearly defined. A solution to this problem is transforming organic P into inorganic forms of P (Rittmann et al., 2011). An important method that is used to achieve this is precipitation of WW effluent where most often P is recovered in the form of calcium phosphate or struvite (for more information on struvite and its chemical properties, see section 6.3.1.1).

Despite such options, implementation on a commercial, larger scale has yet to take place (Cordell et al., 2009; Schröder et al., 2010). There are various difficulties with recovery and recycling of waste streams. Schröder et al. (2010) stress that the concentration of P needs to be sufficient for recovery as this determines the economic feasibility of recovery, storage and transport. Moreover, due to the required recovery techniques, products such as struvite are not yet sufficiently price competitive compared to current conventional sources of P on the market such as diammonium phosphate and superphosphate (Balmér, 2004; Rittmann et al., 2011). The potential increases in P prices might therefore be an important incentive to stimulate more large-scale adoption of recovery and recycling practices (van Enk et al., 2012).

For large scale implementation there is also a need for institutional adjustments to accompany possible infrastructural changes. However, several authors stress whilst P issues are a pressing matter, it currently receives little attention on the political agenda (Cordell et al., 2009; Keyzer, 2010). Furthermore, there are various actors involved and related to P, yet governance or policies are missing to address and ensure the long-term sustainable use of P for global food production (Cordell, 2010). In subchapter 4.4 it is examined how these identified global issues are related to the situation in the Netherlands.

4.4. Phosphorus in the Netherlands

4.4.1. The national P balance

Like the majority of European countries, the Netherlands does not have any economically viable phosphate resources, which is why the country is entirely dependent on the import of mined P from abroad (van Enk et al., 2012). For 2005, the P balance for various subsystems in the Netherlands was calculated by means of a material flow analysis (MFA) (Smit et al., 2010). The subsystems included agriculture (arable farming, grazing animals and intensive animal husbandry), industry (feed, food and non-food products), households and waste disposal. According to this systematic assessment, the total import of P accounted for some 108 Mkg (million kg[43]) P, which includes both organic sources of P such as food and animal feed as well as inorganic P sources (e.g. mineral fertilisers and feed additives). This number increased to 115 Mkg P in 2008. Approximately 45% of the P imported into the Netherlands was again exported in the form of food for human consumption, as manure, and to a lesser extent as non-food products and waste. As a result, the national balance surplus amounted to some 60 and 51 Mkg P in 2005 and 2008, respectively[44]. Table 4-3 gives a more detailed overview of the national P balance for the years 2005 and 2008.

	Subsystem	Products	2005	2008
Import	Agriculture	Fertiliser	21.0	12.0
		Living animals	0.21	0.22
	Industry	Feed	50.4	60.1
		Food	28.0	31.1
		Non-food	1.4	3.3
		Feed additives	7.2	8.1
	Total import		*108.2*	*114.8*
Export	Agriculture	Manure	7.0	12.8
	Industry	Food	37.5	47.6
		Non-Food	1.3	1.2
	Waste	Waste	2.7	2.0
	Total export		*48.5*	*63.6*
	Balance surplus		***59.7***	***51.2***

Table 4-3: National phosphate budget in 2005 and 2008 in the Netherlands (Mkg P/yr) Source: Smit et al., 2010.

In other words, around half of the total amount of imported P remains in the country in one form or another. What are the reasons for that and where does this remainder end up?

[43] 1 Mkg equals 1,000 tonnes.
[44] According to De Buck et al. (2012), the reduction of the P surplus was a result of the decreased use of mineral fertilisers and the increased export of manure, combined with the increased net import of the industry.

4.4.2. Livestock farming and P-saturated soils

The bulk of the national P surplus can be attributed to the large amounts of imported animal feed into the agricultural sector, which is typical for those countries, including the Netherlands, Belgium and Denmark, that produce vast quantities of meat, poultry and dairy products (relatively to the amount of agricultural land available) and who depend on the import of animal feed to feed their livestock and poultry (van Enk et al., 2012). Due to intensive livestock farming, the production of manure in the Netherlands amounted to some 85 Mkg of P in 2010, of which slightly more than half was used as fertiliser at the farms where it was produced. The other half was sold to the agricultural sector via the manure market (40%), exported abroad (30%) or processed (incinerated or taken up by other sectors in the Netherlands) (approx. 20%), 10% were taken up outside the agricultural sector (de Koeijer et al., 2010). For 2 to 3.5 Mkg of P, there were no purchasers found. In general, such a surplus would then come on the manure market in the following year, increasing the pressure on the manure market and thereby resulting in relatively high charges for manure removal.

The highest amount of P “production” from animal manure occurs in areas with high concentrations of livestock farming: the eastern part of Noord-Brabant and the Western Veluwe (CBS et al., 2013). Since farmers have to pay for manure removal via the manure market, they will instead apply the maximum amount of manure that is permitted by law[45] onto their own land. Besides manure, Dutch farmers apply another 18 Mkg of P in the form of mineral fertiliser in 2006 (Vergouwen, 2010). Consequently, and taking account of other flows as well, half of the national P surplus accumulates in agricultural soils as less available forms of P[46] (Smit et al., 2010). Soil analyses conducted in the 1990’s show that 56% of the arable land in the Netherlands is therefore saturated with P (see Figure 4-4). According to calculations by Van Enk et al. (2012), the accumulated amount of P in the topsoil layer is equal to about 40 years of the current consumption of inorganic P fertilisers. It is estimated that fertilisation with P would actually not be required at all on 35% of the agricultural land in the Netherlands.

[45] The maximum amount of manure that is permitted to be applied on land is regulated in the “Usage norm for manure” (“gebruiksnorm voor dierlijke mest”). In general, this norm prescribes that no more than 170 kilo of nitrogen per hectare may be applied to agricultural soils (derogation companies may use 250 kilo of nitrogen per hectare). Next to this usage norm, there are the nitrogen usage norm and the phosphate usage norm, which prescribe different amounts depending on the type of land that is to be fertilised. For more information, see: http://www.drloket.nl/onderwerpen/mest/dossiers/dossier/gebruiksruimte-en-gebruiksnormen/gebruiksruimte-dierlijke-mest-en-derogatie/berekening-gebruiksruimte-dierlijke-mest

[46] Phosphate tends to co-precipitate with various minerals that naturally occur in the topsoil layer and to adsorb on their surfaces. The primary phosphate mineral, apatite, is slowly broken down by weathering and subsequently transformed into a fixed and occluded phosphate pool, which is hardly available for plants. The longer phosphate remains in the topsoil, the more of it co-precipitates and adsorbs and the less will therefore be available for uptake by plants. According to Van Enk et al. (2012), this process is the reason why only 60% of the agricultural P consumption in the Netherlands is effectively used for the production of crops, animal feed and animal products.

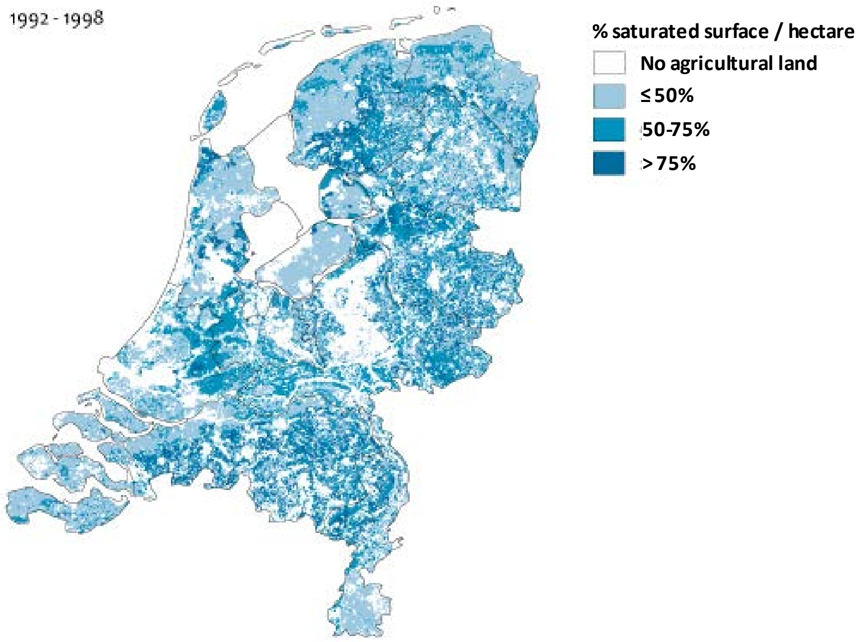

Figure 4-4: Phosphorus saturation of agricultural soils in the period 1192-1998, the Netherlands. Source: CBS et al., 2008.

4.4.3. Eutrophication of water bodies

While one half of the national P surplus accumulates in agricultural soils and contributes poorly to crop food supplies, the other half accumulates in water bodies (groundwater, rivers, lakes, etc.) and is sequestered. The excess P in surface water in the Netherlands originates equally[47] from the leaching and runoff from agricultural land on the one hand and from the effluent of WWTP[48] on the other hand (Smit et al., 2010). As explained in section 4.3.5, this contributes to eutrophication of water ecosystems and can have detrimental effects on the quality of drinking water reserves. Large parts of the surface water in the Netherlands do not comply with desired the European Water Framework Directive (2000/60/EC), among others due to their high amount of nitrogen and P[49] (CBS et al., 2012a). Relatively high concentrations of P in surface water, originating from agricultural land, occur not only in clay- and peatlands (Western and Northern parts of the country with soils that are by nature richer in nutrients), but also in sandy areas. Especially the sandy areas in Noord-Brabant and the Veluwe area are saturated, as mentioned earlier, yet simultaneously hold important drinking water reserves (CBS et al., 2013). The accumulation of P in the sandy areas has reached a critical level where it is leached into groundwater and thereby affecting drinking water quality (Vergouwen, 2010).

[47] In 2005, the total emission of P to surface water amounted to some 7 Mkg P. Approximately 47% (3.3 Mkg P) of this could be attributed to leaching from agricultural land, while the remainder originated from non-intercepted P from communal and industrial WWTP (Smit et al., 2010).
[48] About 75% of the residential wastewater (WW) is treated, while the remaining quarter drains into surface water.
[49] Regarding the standardisation of nutrients in surface waters, critical concentrations (maximum acceptable concentrations – MAC values) for standing waters (primarily lakes and ponds) have been defined, since they are most sensitive to eutrophication. Summer averages must not exceed 0.15 mg/l total-P. These values can differ for water types less sensitive to eutrophication, such as small water bodies and large rivers that are located further upstream. Further, the European Water Framework Directive differentiates between natural bodies of surface waters and heavily modified or artificial bodies of water, for which it defines a "good ecological status" (GES) and a "good ecological potential" (GEP), respectively. Next to the MAC values, there are thus also GES and GEP values for the different water types . For a detailed list of the values, see Schoumans et al. (2008).

4.4.4. Accumulation of toxic metals

As outlined above, most mineral P fertilisers contain rather high concentrations of toxic heavy metals such as cadmium. This issue is increasingly becoming relevant in the Netherlands: Since these toxic metals also tend accumulate in the topsoil layer, a considerable amount of agricultural soils in the Netherlands is significantly enriched with cadmium and zinc and thus pose a risk to food safety. Especially in the central and northern parts of the Netherlands (sandy soils), this is mainly related to agricultural practices (van der Veer, 2006).

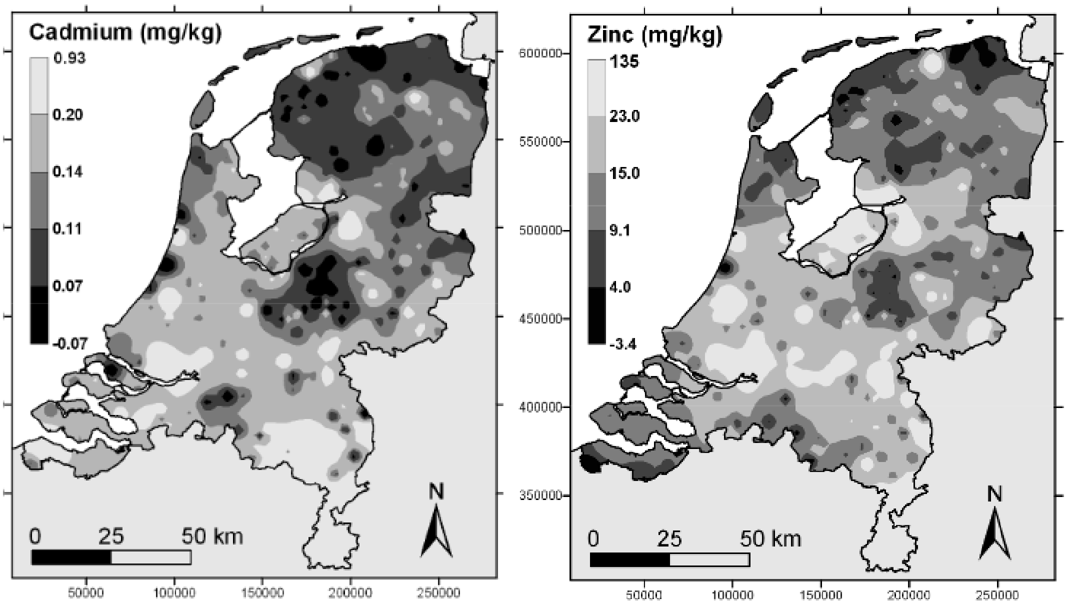

Figure 4-5: Density corrected absolute enrichment of cadmium (Cd) and zinc (Zn) (mg/kg) in the Netherlands in 2006 van der Veer, 2006.

4.4.5. Other P losses

Next to the described losses of P (leaching and runoff, accumulation), Smit et al. (2010) point out that there are so-called 'missed opportunities': potentially recoverable P-flows, which are however not returned to agricultural land. One example is communal sewage sludge that is currently mainly incinerated[50], among others due to concerns of contamination with heavy metals. Also, the performance of water treatment plants is only benchmarked in terms of the effluent quality (not in terms of how much P they *recover*), which is why they primarily aim to generate an effluent that contains as little P as possible in order to minimise the pollution of surface waters with nutrient. In Dutch WWTPs, some 14 Mkg of P are annually removed from residential and industrial WW.[51] Having in mind the amount of imported P that is utilised as mineral fertiliser (18 Mkg P in 2006), it becomes apparent that P recovery from WW could significantly contribute to closing the P loop (Vergouwen, 2010). Another major loss of P in the Netherlands is through the destruction of dead animals and slaughter waste, particularly the bones that are rich in P. Due to hygiene regulations (in relation to BSE 'mad cow' disease), almost half of the P in bones is incinerated and by that P is lost since ashes are not used. Moreover, the practice of incinerating and landfilling of P containing

[50] In the Netherlands, about 60% of the sewage sludge is incinerated (Kalmykova et al., 2012). The incinerated ash is subsequently used in the cement industry, road construction, and the brick industry (van Enk et al., 2012)
[51] About 80% originates from human faeces and urine (Vergouwen, 2010).

residues from the food and feed industry as well as from households (such as food or garden waste[52])[53], are other factors that explain the low efficiency of P use in the chain from mine to fork.

In the light of the large quantities of P that are either lost or not recovered, it becomes apparent that P is not yet treated as a valuable and finite resource in the Netherlands. Smit et al. (2010) point out that although "it appears as if the Netherlands is less dependent on mineral P-fertiliser (because of its surplus) it must be realised that most of the P-rich feed that is imported from other countries (e.g. Brazil), could only be produced with the input of fertiliser itself. Therefore, Dutch agricultural activities are equally dependent on the use of mineral P-fertiliser."

4.4.6. Possibilities for more sustainable phosphorus use

In spite of the aforementioned issues, there have been positive developments with regard to P in the past decades, too. In an attempt to respond to the large P surplus and to reach a balance between input and output of P, the Dutch government in 1984 and 1987 introduced regulations[54] that were, among others, dedicated to reduce the amount of phosphate from animal manure. This led to a gradual decrease of the P surplus on agricultural land (52% between 1986 and 2011, see Figure 4-4) (CBS et al., 2008). The reduction was further accelerated by a decreasing consumption of inorganic sources of P such as feed additives[55] and detergents as well as mineral P fertiliser. Furthermore, the standards for P of livestock were lowered. Another reason for the decreased consumption of inorganic P sources was the reduction of P in detergents so as to prevent eutrophication of surface waters. All in all, 75-89% of the lowered P input in freshwater streams since 1986 can be attributed to efforts from industry and communities (including process improvements in WWTPs), and only 12% to measures undertaken in agriculture. In 2006, the Dutch government replaced the existing regulations through a new legislative framework (Fertiliser Act), which requires farmers to further reduce their application of major nutrients such as P (van Enk et al., 2012). To enable this, there are numerous actions currently carried out, which are however focused on agriculture and thus less relevant for the scope of thesis.[56]

[52] In Dutch GFT-afval (groenten-, fruit- en tuinafval)

[53] According to Smit et al. (2010), some 10.4 tonnes and 7.5 tonnes of P are incinerated and landfilled, respectively, on an annual basis in the Netherlands. For their study the reference year of 2005 was chosen.

[54] "Beschikking Superheffing" (from 1984) and "Mestwetgeving" (from 1987)

[55] The decreased need for feed additives was a result of the introduction of phytase in feed for pigs and chickens. Phytase is an enzyme that increases the uptake of P from feed, so that 25% less P has to be added to the feed (Schoumans et al., 2008)

[56] They include: reduced phosphate content in feed concentrates; reduced import of dietary phosphates; reduced use of phosphate from mineral fertilisers; treatment of manure and other biosolids; P recovery (for a more detailed overview, see Van Enk et al. (2012).

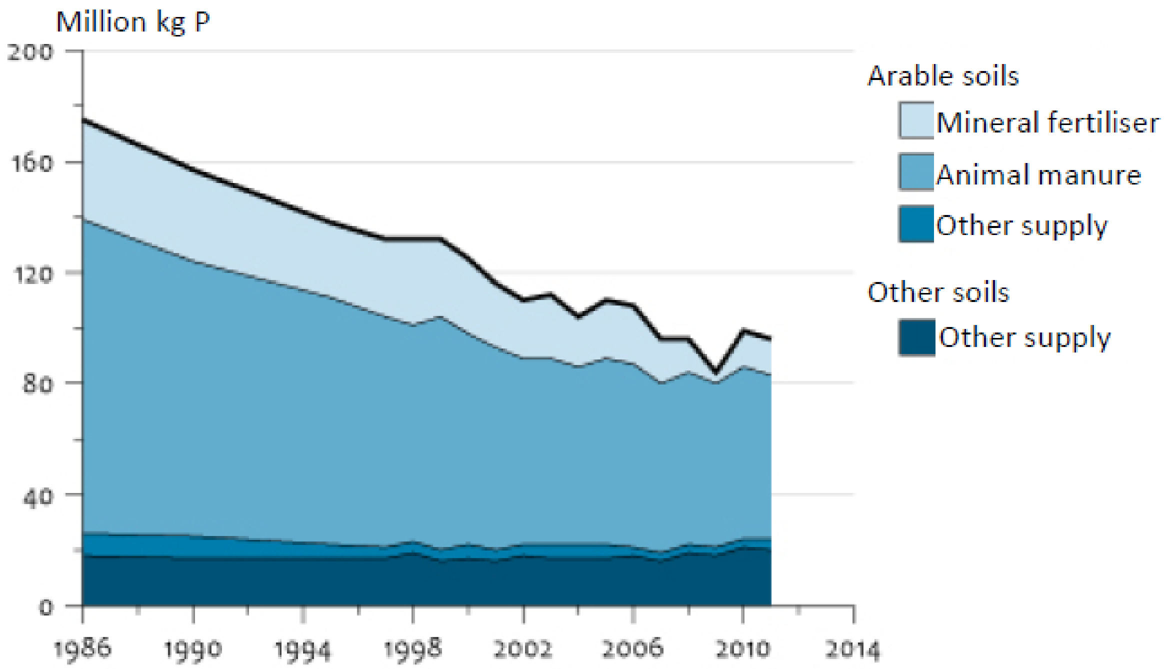

Figure 4-6: Uptake of phosphorus on agricultural soils and groundwater, historical development during the last three decades CBS et al., 2012b.

All these measures make clear that government policy has so far mainly focused on balancing the use of P by making its use more efficient, but were not directed toward recycling of available P sources as such. However, this is what a more sustainable use of P requires as well. So far, most of the recycled P in the Netherlands originates from animal manure, by-products from food production as well as plant and animal by-products. Other potential sources for the recovery of P include human urine and WW. P from human urine can be precipitated by evaporation or after precipitation into struvite. This however requires a modified sanitation system that separates urine and faeces. Several projects to this end are currently in place on a local scale.[57] A major hindrance to this practise is that struvite, although the technology is fully available, is still not permitted as an agricultural fertiliser in the Netherlands, while it is already widely used in Japan for example. Studies have shown that struvite can have better fertilising qualities than conventional commercial fertilisers (van Enk et al., 2012).

As explained in 4.2.6., P from WW is usually recovered after precipitation into struvite or calcium phosphate. In the Netherlands, there is currently only one plant that produces calcium phosphate pellets from sewage influent (Geesmerambacht sewage works). Until 2012, the phosphate recovered from these pellets used to be added to the phosphate rock feed at the Thermphos furnace operation in Vlissingen (ibid.), the main production site of Thermphos International. The company produced different P containing products such as P derivatives, phosphoric acid, phosphates and phosphonates and had the ambition to completely use waste streams (such as sewage sludge and

[57] An overview of projects on 'New Sanitation' systems in the Netherlands supported and carried out by STOWA (Foundation for Applied Research on Water Management) is given here: http://nieuwesanitatie.stowa.nl/Projecten/index.aspx?pId=1340

bone meal) in the production process by 2020. However, Thermphos was declared bankrupt in 2012 (Thermphos International B.V., 2012).

If the recycling rate of P is to be increased in the Netherlands, current regulation both at the national and EU level, for instance regarding the use of struvite in agriculture, needs to be reviewed. Smit et al. (2010) underline that the recycling of P will have consequences for agriculture. In the short term, the national P surplus will be higher for agriculture. This will require adaptations in one way or another, such as more export of manure or recycled P, less livestock, less fertiliser use, or less imported animal feed.

4.5. Conclusion

This chapter explained sustainable management of P is crucial. It is essential to life on earth, plays a key role in food security, cannot be substituted by any other element and the most important source of P (phosphate rock reserves) is eventually finite.

Despite its necessity and concerns over (economic) scarcity, there is no sustainable management of P at present. The most crucial issues surrounding P that threaten sustainable use of this resource are a growing demand for P, whilst simultaneously large amounts of P are (unnecessarily) lost. In addition, these P losses into water bodies have shown to have detrimental effects on the environment. Especially in the Netherlands, which has saturated P soils, eutrophication is a pertinent issue. Beyond the quantity of P, it is also the quality of P that causes concern worldwide and in the Netherlands. With uranium and cadmium being extracted together with P from phosphate rock to produce fertilisers (among other), a slight percentage is said to be present in these fertilisers. This results in a contamination of soils - affecting food safety.

There are technological possibilities to further P reuse and recycling, yet these technologies are not implemented on a larger, commercial scale (yet). If P issues were to be put stronger on the political agenda, this might stimulate more large scale implementation.

5. Introduction into the case-study: Wageningen

5.1. Introduction

In this chapter, the chosen case-study for analysis is shortly introduced in order to provide context to the research conducted. Thereby, allowing a better understanding of the relative size of the city, the type of population and the surrounding character of the region in which it is situated. First, there is a short introduction into Wageningen, its history and demographic features. Thereafter, its regional context is described. Finally, a conclusion of the main findings is presented.

5.2. Wageningen

Wageningen is a small town in the province of Gelderland, the Netherlands, covering an area of 32.36 km^2. In 2012, it counted 37,049 inhabitants with a population density of 1,215 inhabitants per km^2 (CBS, 2012). Wageningen experiences population growth, as the population has grown to 37,407 inhabitants per January 2013 (Gemeente Wageningen, 2013a). This is below the country average which was around 41.000 inhabitants per city in 2013 (CBS, 2013a). In Wageningen, around 44 % of the inhabitants were younger than 30 as a large part of the population consists of students from national and international backgrounds[58] (CBS, 2012). Studies conducted by the Central Bureau of Statistics in 2008, showed that household incomes in Wageningen are fairly similar to, or slightly above, general Dutch statistics, which makes Wageningen representative of the average Dutch city concerning this aspect (CBS, 2011). Due to its relatively small size (the Netherlands also has cities with a population over 100.000 (CBS, 2013a)) it is expected to be a comprehensible case study for analysis within the time frame of this thesis.

Figure 5-1 Province of Gelderland and location of the city of Wageningen. Source: adopted from CBS 2011.

Although Wageningen until in the twentieth century was known for its brickworks and cigar industry (Gemeente Wageningen, 2013b), it is currently an important part of 'Regio FoodValley' and considered a knowledge hub on food, health and life sciences (Regio FoodValley, 2013a). This

[58] In 2012, the total amount of students was around 7,700 of which 5,330 live in Wageningen (Apollo, 2012).

development was kick-started in 1876, when a school for agriculture was built, that attracted knowledge and people. The school of agriculture grew into what is now known as Wageningen University – an internationally acclaimed higher education institution with a focus on food, agriculture and life sciences (Gemeente Wageningen, 2013b; Wageningen UR, 2013a). Together with associated agricultural research institutes such as Alterra and IMARES, Wageningen University and Research Center (WUR) is formed (Wageningen UR, 2013a). In addition to WUR, Hogeschool Van Hall Larenstein - another higher education institution focusing on similar topics – is also located in Wageningen. Furthermore, headquarters of Food Valley NL are also based in Wageningen. Food Valley NL is an overarching organisation that aims to stimulate innovation in the agrifood sector by bringing business together with academic research and governmental institutions (Food Valley NL, 2013)[59]. This unique context allows the municipality to profile itself as city of life sciences (Gemeente Wageningen, 2013c). For more information on the history and development of Wageningen, see the book '*Geschiedenis van Wageningen*'[60].

5.3. Region

In addition to being a hub of academic knowledge, Wageningen is positioned in an agricultural setting and closely located to municipalities that are involved in food production, consumption and innovation. The municipality of Barneveld specialises in intensive livestock industry and is known worldwide for its expertise and innovation on poultry farming, egg-sorting machines and meat processing. Nijkerk has many agrifood businesses, such as Arla Foods: a company that specialises in the production of dairy products. The municipality of Ede is more similar to Wageningen, as it has an emphasis on building knowledge. The focus is not on academic research, but instead providing young people with practical knowledge. Moreover, an important international research institute on food, the NIZO Food Research, is also based there (Regio FoodValley, 2013a). Due to this local context and focus, Regio FoodValley was established. This is a collaboration between eight municipalities, namely: Wageningen, Ede, Barneveld, Nijkerk, Renswoude, Rhenen, Scherpenzeel en Veenendaal (see Figure 5-2).

[59] For more information on parties involved in this initiative see http://foodvalley.nl/Paginas/Food%20Valley%20Society/Leden.aspx

[60] Gast, K., Kemkamp, B., Klep, L. 2013. *Geschiedenis van Wageningen*, eds. K. Gast, B. Kemkamp, L. Klep, 1-384. Wageningen: Blauwdruk (ISBN 978-90-75271-74-4).

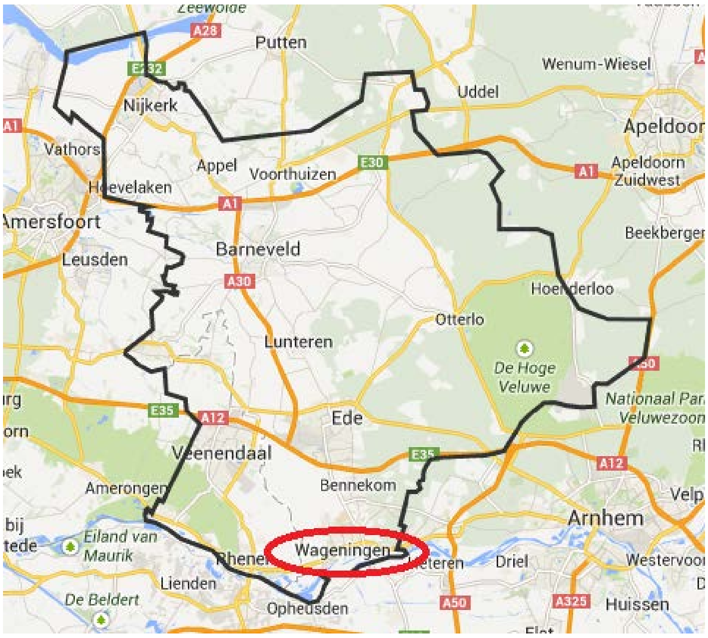

Figure 5-2: The boundaries of Regio FoodValley. Source: Regiokaart adapted from Regio FoodValley, 2013.

The aim of Regio FoodValley is to further strengthen, facilitate and stimulate the region's strategic position concerning food related knowledge and innovation by actively inviting new talent and businesses to settle in the region. As its vision for the region, Regio FoodValley focuses on providing a facilitating role for companies, accommodate between required labour and education, improve mobility and accessibility to the region, innovation in the agricultural sector and enhance quality of the living environment (Regio FoodValley, 2013b, 2013c).

5.4. Conclusion

Concluding, the municipality of Wageningen is fairly small and has a history in education with an emphasis on agricultural and environmental sciences. This role has further expanded throughout the years and resulted in Wageningen to become known as a knowledge hub on the afore-mentioned topics. The region in which it is situated also has an agricultural focus, where there is active collaboration between the municipalities to further strengthen the region's unique identity.

6. Results

6.1. Introduction

The results of the quantitative and qualitative data collection are described in this chapter. Parallel to the order of the sub-research questions, this chapter first addresses the baseline (concerns the year 2012, see section 3.3). Within subchapter 6.2 of the baseline, the physical infrastructure of Wageningen with respect to wastewater (WW) and municipal solid waste (MSW) is shortly explained. This provides a general understanding of the various pathways of phosphorus (P) through the system. Thereafter, the main outcomes of the calculations and the modelling of the substance flow analysis, which illustrate the current performance of Wageningen with regard to P reuse/recycling, is outlined. Second, the results on alternative strategies are presented in section 6.3. Here those findings that affect the feasibility of alternative strategies for the MSW and WW system are addressed first. Thereafter, the impact of the identified feasible alternatives on P reuse and recycling is estimated through calculation. Finally, a conclusion of the main findings is presented in section 6.4.

6.2. Baseline

6.2.1. Infrastructure

For the description of the infrastructure, the collection system and the treatment process are separately addressed. Although the treatment process of WW and MSW are officially outside the defined system boundaries of Wageningen, it is included in this thesis so as to understand the destination of P. In the description of the infrastructure, the waste treatment processes (especially of MSW) are only touched upon briefly and will be explained more in detail in section 6.2.2 that elaborates on the destination of P.

6.2.1.1. Wastewater

A review of SFA studies on P by Cordell et al. (2012), showed that in previous SFA studies focusing on P in urban areas, most of the P entering the urban area ends up in WW. This illustrates the importance of this waste flow and is necessary to understand and identify the pathway of P through it.

Wastewater collection system

The fraction of P in food that ends up in municipal WW enters it via two streams: black water (BW: P is found in urine and faeces) discharged via the toilet, and grey water (GW: P is found in food waste), discharged through the sink. Overall, households and non-households in Wageningen are connected to a centralised sewer system, where both streams are combined. Generally, all WW is discharged through the sink and a flush toilet. However, it must be noted that vacuum toilets, which require much less water than current flush toilets[61], are starting to make their way into Wageningen - albeit very minimal. The most large scale implementation of vacuum toilets (18) so far, is at the NIOO building: an office that is home to the Netherlands Institute of Ecology (Everard, 2013; NIOO-KNAW, 2011). Although the NIOO building is currently officially connected to the sewer system, NIOO aims

[61] Where a regular flush toilet is said to use approximately 5.9 litres of water per flush compared to only 0.5-2 litres per flush for a vacuum toilet (Foekema et al., 2007; Mels et al., 2005).

to be completely autarkic in handling and treating its BW[62]. This system in NIOO is based on the concept of Decentralised Sanitation and Reuse (DESAR). DESAR concepts separate different WW streams at source for optimal reuse and recycling of water, energy and valuable nutrients, whilst reducing emissions to the environment (Mels et al., 2005; Zeeman et al., 2008). In DESAR systems, vacuum toilets are a key part of the infrastructure, as less water results in a more concentrated stream of nutrients in BW. Thereby making P recovery and recycling economically more feasible (Schröder et al., 2010). For more information on DESAR concepts see section 6.3.1.1.

In addition to NIOO, the municipality of Wageningen aims to install vacuum toilets in the renovated city hall, according to Harry Post, project manager sewerage and water management at the municipality of Wageningen (personal communication, October 30, 2013). The incentive driving the municipality is to partly set a more sustainable example, whilst simultaneously reducing water use.[63] More information on DESAR and vacuum toilets are presented in the subchapter 6.3.

Apart from the afore-mentioned frontrunning projects in Wageningen, a flush toilet connected to a centralised sewer is the predominant collection system for black water. Currently, most of the centralised sewer system is combined (WW being mixed with storm water). However, the municipality aims to increase the separation of WW and storm water collection (Arcadis, 2010). Figure 6-1 depicts the current sewerage system, where currently around 30 % of separated sewer is implemented – equal to a length of 54 km (areas marked brown) (van der Molen, 2012). This separation of storm water and WW collection, takes place whenever the old combined infrastructure needs to be replaced, or new building areas are constructed. The total length of the sewage system under administration of Wageningen is around 180 km. At present, the replacement towards a separated sewer system is approximately 2 km per year. Depending on the quality and age of the sewage pipes, replacement is often only necessary after 60 years. Most of the infrastructure was implemented in the 1970-1990's and it is thus estimated this is only up for replacement in 2030-2040 (Arcadis, 2010; van der Molen, 2012). Whenever implementation of a new separated system causes too much nuisance or is considered too costly, relining of the sewage pipes is also applied. Relining refers to the insertion of a new plastic pipe in the old piping system. In the case of new building plots, a separated sewer system is implemented or (depending on the situation) a sustainable alternative (Arcadis, 2010).

Since not all the sewage from Wageningen can reach the WWTP through the works of gravity, Wageningen also has pressure sewage, several pump wells, and pumping stations (van der Molen, 2012). To reduce any risks that might occur in case of sewer overflow, Wageningen has built 3 storage settling tanks in 2005 that allows the excess polluted water to settle, which avoids direct discharge to any nearby water bodies (Arcadis, 2010). The responsibility of the collection of WW from buildings as well as ensuring proper transport through the sewage system is in the hands of the municipality (Arcadis, 2010).

[62] For more information on this specific system in NIOO, see http://www.nioo.knaw.nl/en/among-ecologists/poop-eating-algae

[63] The reduced water use of vacuum toilets means that the choice for vacuum toilets can be a direct cost saver on the use of water. This an important driver, since there is an administrative agreement between the Dutch Ministry of Infrastructure and Environment, the water boards and all municipalities to reduce costs related to the water chain in 2020 by € 380 million Euros per year (Dutch Ministry of Infrastructure and Environment, 2011; Harry Post, personal communication, October 30, 2013).

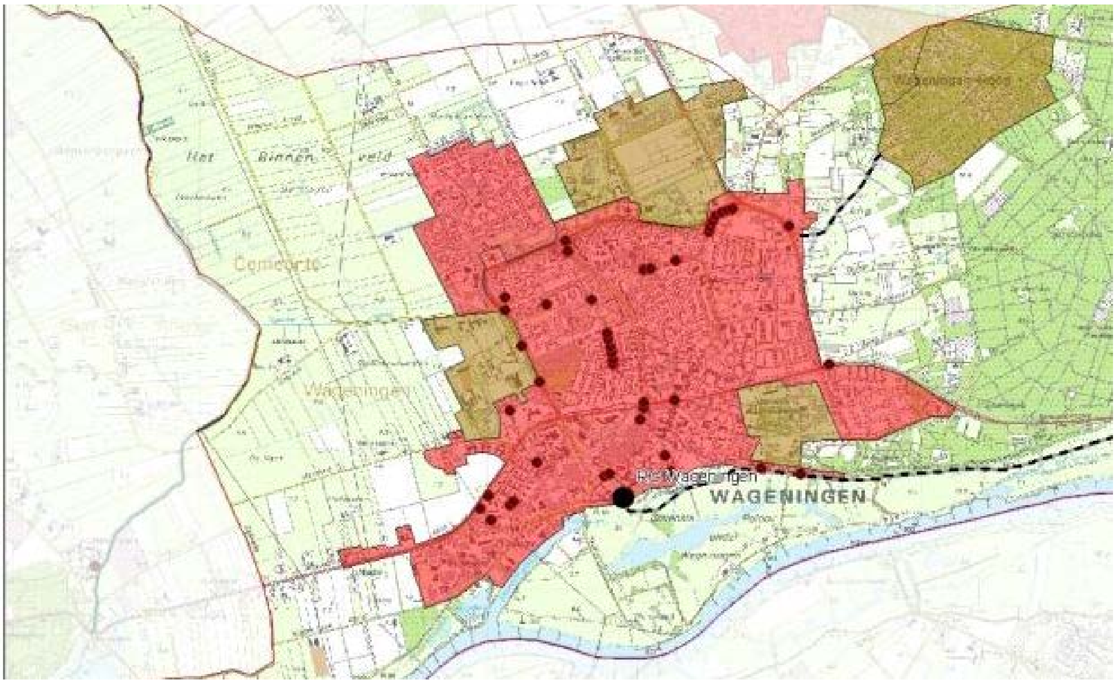

Figure 6-1: Overview of the sewer system in Wageningen where red marks combined and brown marks separated sewer system. Source: Adapted from Van der Molen 2012, Annex 1, map of catchment area.

Wastewater treatment

The WW of Wageningen is transported through the sewer system to a wastewater treatment plant (WWTP) in the nearby town of Renkum. Apart from Wageningen, this WWTP thus also receives WW from the municipality of Renkum. A schematic overview of the WW treatment process is presented in Figure 6-2 and an aerial view of the actual treatment process is depicted in Figure 6-3.

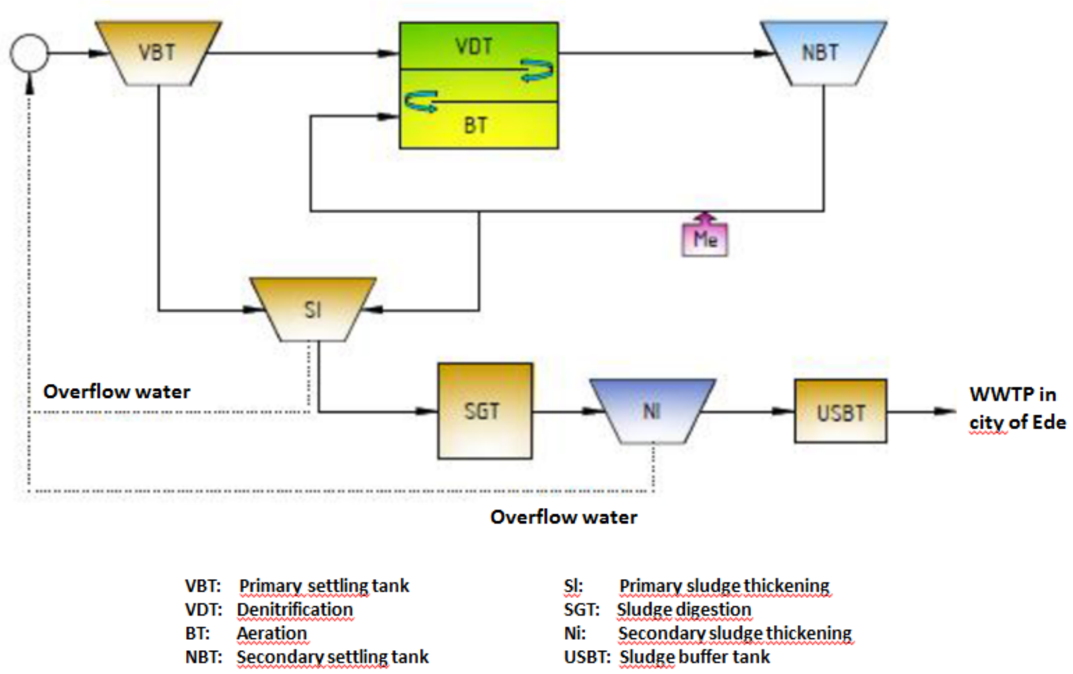

Figure 6-2: Schematic overview of the wastewater treatment process at the WWTP in Renkum. Source: Adapted from Van der Molen 2012.

Figure 6-3: Aerial view of WWTP in city of Renkum. Source: Adopted from Van der Molen 2012, cover page.

The P in WW is found in water line and sludge line. The technological scheme presented in Figure 6-2 above is further explained below:

First, there is preliminary treatment where the coarse particles are removed from the WW through screens. Furthermore, most of the grit (mineral, heavier particles such as sand) particles are captured by a sand trap. From there, the WW flows to a primary settling tank, where parts of the settleable solids are removed from the WW. The produced primary sludge at the first settling stage, is sent to the primary thickener. The scum that is formed at the surface is collected at the surface and periodically diverted to the anaerobic digestion stage (anaerobic digestion is further described below). Thereafter, the WW is then treated by activated sludge (denitrification and aeration takes place) and from there the WW is sent to a secondary settling tank. After the second settling step, the effluent is discharged on the river Rhine. During the secondary settling stage, secondary sludge is produced. A part of the secondary sludge is returned to the activated sludge stage. Excess sludge is extracted from this return sludge and sent to the primary thickener where it is joined with the earlier produced primary sludge. After primary thickening, all sludge is anaerobically digested to partly stabilise the sludge and extract biogas for the purpose of energy recovery. Thereafter, the sludge goes to a secondary thickening stage and finally to a buffer tank for storage. The sludge is then transported by trucks to the WWTP in Ede, where the sludge is dewatered by centrifuges (van der Molen, 2012). From there, the sludge is collected by the sludge processing company GMB BioEnergie, that uses the technique of bio-drying[64] of sludge in tunnels according to Ellenbroek (2008) and Martin Wilschut, manager GMB water technology at GMB BioEnergie (personal communication, October 25, 2013). The produced end-product is sold as biofuel (biogranulate) to power plants mostly in Germany and partially in the Netherlands (GMB BioEnergie, 2013).

[64] For more information on this technique see http://www.gmb.eu/images1/gmb/data/pdf/biodrying%20paper%202013.pdf

6.2.1.2. Municipal solid waste

Phosphorus in food is found in three different MSW streams: mixed waste, organic waste and 'swill'. The swill waste stream differs from 'organic waste' (GFT), as it only concerns commercial food waste and does not contain garden waste. Furthermore, it is often more liquid than the separated 'organic waste' stream[65]. Whereas all WW is collected, transported and treated via a centralised system, the MSW system is much more decentralised. The physical infrastructure for the collection of all waste streams is diverse and the waste collection, transportation by road and treatment are performed by various parties, which make the MSW system much more complex. Therefore, households and non-households are separately addressed in this subchapter.

Municipal solid waste collection system: Households

The P in food originating from households is disposed of in the mixed and organic waste stream. The P found in mixed and organic waste is from food waste related to human consumption and waste related to pet consumption (pet excreta and wasted pet food). The physical infrastructure for the collection of the afore-mentioned household waste streams is dependent on whether the buildings are high-rise or low-rise. Each low-rise building has separate containers for mixed (240 L) and organic waste (140 L). Both waste streams are collected once in two weeks. High-rise buildings have a shared collection container. This is often placed above ground, but in the city centre and new high-rise buildings, below ground. Unfortunately, some high-rise buildings have no separate organic waste container (Gemeente Wageningen, 2012a). Especially people in high-rise buildings are found to perform poorly on the separation of organic waste (Gemeente Wageningen, 2012a).

The produced mixed and organic waste from households is all collected by the municipal waste collector ACV group, of which the municipality itself is a shareholder (Gemeente Wageningen, 2012a). However, it must be noted that a minor fraction of the organic waste ends up in tanks for home-composting. Out of the total 20.946 households in Wageningen, 150 are estimated to have such a home-composting tank (CBS, 2012; Gemeente Wageningen, 2012a).

The municipality also decides which company is contracted for treating the household waste. Currently, the organic waste is sent to a waste processor company in Enschede: Twence (Gemeente Wageningen, 2012b). According to Wim de Jong, senior advisor strategy and policy at Twence (personal communication, November 8, 2013), the household organic waste is first anaerobically digested and the digestate is thereafter redirected into the composting lines. The compost is presumed to be destined for the domestic market only (Wim de Jong, personal communication, November 8, 2013). The collected mixed waste is incinerated at the waste processing company ARN in Weurt.

Municipal solid waste collection system: Non-households

For non-households, the relevant waste streams that need to be considered are mixed waste, organic waste and swill, as all these waste streams contain P in the form of food waste. For households, the municipality has a legal obligation to collect the waste. Here, inhabitants have no

[65] The 'swill' waste stream is usually a mix of cooking oil, liquid food waste, prepared and unprepared kitchen waste and is thus often associated with the supermarkets, hospitality sector and company catering services (therefore explained as commercial food waste and residues)

influence on who collects or processes their waste (Gemeente Wageningen, 2012a). The non-household sector however, has the freedom to decide who to contract for handling waste streams. The choice for contracting a waste collection and processing party is influenced by the type of waste produced. For instance, the hospitality sector (consisting restaurants, hotels etc.) is marked by the waste stream 'swill' (cooked and prepared food waste), which requires a different waste processor than a small office with little to no food waste. Of course, also the collection frequency and the type and size of containers used, is tailor made to fit the amount of waste produced. According to ACV group, the municipal waste collector, the following waste collection and processing companies are active within Wageningen to collect company waste: ACV group itself, Van Gansewinkel, Van Beelen, Van Happen, Sita, Dusseldorp, Ter Horst, Remondis, Van Brenen and Wolfswinkel (Anja Spee[66], personal communication, November 15, 2013). In addition to these waste collectors, ACV group outsources the collection of swill to the companies Rotie and ReFood. The size of containers that companies require can range from 120 L to 2500 L (Anja Spee, personal communication, November 15, 2013 and Marga van het Erve[67], personal communication, December 12, 2013). Although it proved difficult to get exact, solid data on the destination of food waste in the non-household sector, the assumption is made that food waste is partly separated at source and processed in the form of organic waste (GFT) or swill. In the case of supermarkets, a minor fraction is also presumed to be donated and find its way to food banks or charity. Most of the food waste however, does appear to end up in the mixed waste stream. This division per subsector is discussed more in detail in section 6.2.2. For more information on the assumptions and decisions made that determined the calculation of flows, see Appendix I: Data collection per subsector of P output.

The final destinations of the collected waste streams are assumed[68] to be as follows: Mixed waste is incinerated. Swill waste is anaerobically digested for the collection of biogas, and depending on the waste processing company, the formed digestate is destined as fertiliser for abroad or incinerated. Finally the collected organic waste stream is assumed to be composted[69]. What this infrastructure implies for the destination of P is discussed in the next section: 6.2.2.

6.2.2. Performance of Wageningen on P reuse and recycling

In order to construct the SFA with the aim of understanding the performance of P reuse and recycling in Wageningen, information is required on (i) the total food related P input of Wageningen, (ii) the P output (in the form of WW and MSW streams) and (iii) final destination of P. For a detailed description of decisions made and sources used for the calculation of all flows connected to various subsectors (households and all processes within non-households) see Appendix I: Data collection per subsector of P output. The level of uncertainty in the calculations made for each flow is also estimated, based on the availability and reliability of the data used (see Appendix III: Uncertainty of flows). Here, the potential dispersion of the final numbers in the SFA is noted as percentages.

[66] Commercial employee at ACV group
[67] Head of Sales Inbound at ACV group
[68] For more information on these assumptions and decisions that determined the destination of P, see Appendix I: Data collection per subsector of P output.
[69] There was no additional information provided on the exact processing of organic waste. At Van Gansewinkel, a waste collection and processing company that collects company waste in Wageningen, GFT is composted (Maarten Duineveld, personal communication, November 22, 2013). This is thus assumed for all GFT collected.

From the data acquired, first the more *specific* findings of the flows and destination of P per (sub)sector are addressed for WW and MSW separately. For the MSW steam, there is a further distinction between households and non-households, since both sectors are marked by different waste streams, amount of P, collection infrastructure (exact pathway of P) and waste treatment process (destination of P). For an overview of all flows and associated quantities see Appendix II: Overview of flows and quantities baseline, Wageningen, the Netherlands. Finally, the specific findings lead to an *overall* picture of Wageningen and its performance on P reuse and recycling from which the most important findings are described.

6.2.2.1. Specific findings P input

The domestic P input from food supply for Wageningen is based on the national Dutch domestic P supply from food in 2011. The latter is estimated at 17.5 Mkg P with a dispersion of 3.3 Mkg according to Bert Smit, researcher at Wageningen University (personal communication, November 27, 2013, publication in preparation). The total amount of domestic P supply from food for the Netherlands[70] was recalculated (downscaled) for the population of Wageningen (by calculating the fraction of population in Wageningen of total population in the Netherlands[71]). This resulted in 51.2 t P/yr, which is depicted in Figure 6-9 as flow 2 (<F2>). The second P input of pet food amounted to 12.4 t P/yr (<F3>). This was calculated by the sum of (i) dietary P intake for pets (see 6.2.2.3) and (ii) assumed fraction of pet food wasted (based on Kalmykova et al., 2012).

6.2.2.2. Specific findings P output: Wastewater

Based on the estimation of dietary P intake, it is calculated that the inhabitants of Wageningen excrete 20 t P/yr, of which approximately 15 t P/yr is excreted at home and 5 t P/yr outside the home. In addition to 15 t P/yr, households are estimated to dispose of 0.1 t P/yr in the form of food waste through the sink, together with another 0.1 t P/yr originating from aquarium fish excreta. Apart from 5 t P/yr in the form of human excreta, it is estimated that non-households also dispose of food waste through the sink, accounting for another 2.6 t P/yr (for detailed description of the calculations, see Appendix I: Data collection per subsector of P output). From the household and non-household sector, all P in WW ends up in the sewer and reaches the WWTP in Renkum. Here, the destination of P is illustrated in Figure 6-4 and found to be as follows: After the primary settling stage, the produced primary sludge contains around 10 % of the total P influent (FAO, 2013a; Mels, 2001) and is sent to the primary thickener. After the second settling step, the effluent, still containing 57 % of the initial P influent, is discharged on the river Rhine. This percentage is based on the known removal efficiency of P at the WWTP (van der Molen, 2012; Waterschap Vallei en Veluwe, 2012). Although there are stricter national legal standards dictating 1 mg/L P in the effluent (Baas and de Zeeuw, 2010; van der Molen, 2012) for removal of P in the WWTPs, these are found not to be applicable to the WWTP at Renkum. Rinus van der Molen (personal communication, October 16), water cycle advisor at water board Vallei en Veluwe, explains this is due to the fact that the WWTP of Renkum disposes of its effluent in the river Rhine. Since this river is marked as a 'national' water and not as an inland water, different standards are applicable. Furthermore, water boards are allowed to deviate from the legal standards per installation, if all WWTPs within the defined area of a water board comply with a total P and N removal standard (Rinus van der Molen, personal communication, October 16, 2013; van der Molen, 2012). After discharge of the effluent, the

[70] Due to a lack of data on 2012, the assumption is made that the number for 2011 is the same as for 2012.
[71] Here, numbers on Dutch and Wageningen population in 2012 were used.

remaining P is found in the so-called 'secondary sludge' (including the P in WW coming from Renkum, this secondary sludge totals 11.9 t P/yr). After release of the secondary sludge from the settling tank, aluminum chloride ($AlCl_3$) is added whenever necessary to improve settleability of sludge[72] (Rinus van der Molen, personal communication, March 13, 2014). $AlCl_3$ is also a strong chemical that binds all remaining P (Emsley, 2000). The use of chemicals such as $AlCl_3$ and $FeCl_3$ (ferric chloride) strongly bind to P, making recovery of P impossible (Emsley, 2000; Rittmann et al., 2011; Martin Wilschut, personal communication, October 25, 2013).

Finally, all sludge of the WWTP, containing 15.9 t P/yr (of which approximately 9.8 t P/yr is from Wageningen[73]), is transported to the WWTP in the nearby town of Ede. In Ede, the sludge is dewatered and then sent to GMB BioEnergie where the sludge is further processed by means of bio-drying. No information was found on the loss of P during the bio-drying process and thus it is assumed that 100 % of P found in sludge is also found in the produced biogranulate that is sold to power plants abroad. The P present in the biogranulate is assumed to be lost through the incineration process as P ends up in the ashes. Since investigating the exact destination of the produced ashes in Germany (containing P) is beyond the scope of this paper, a similar destination of P in ashes is assumed as in the Netherlands (see 'Municipal solid waste' below).

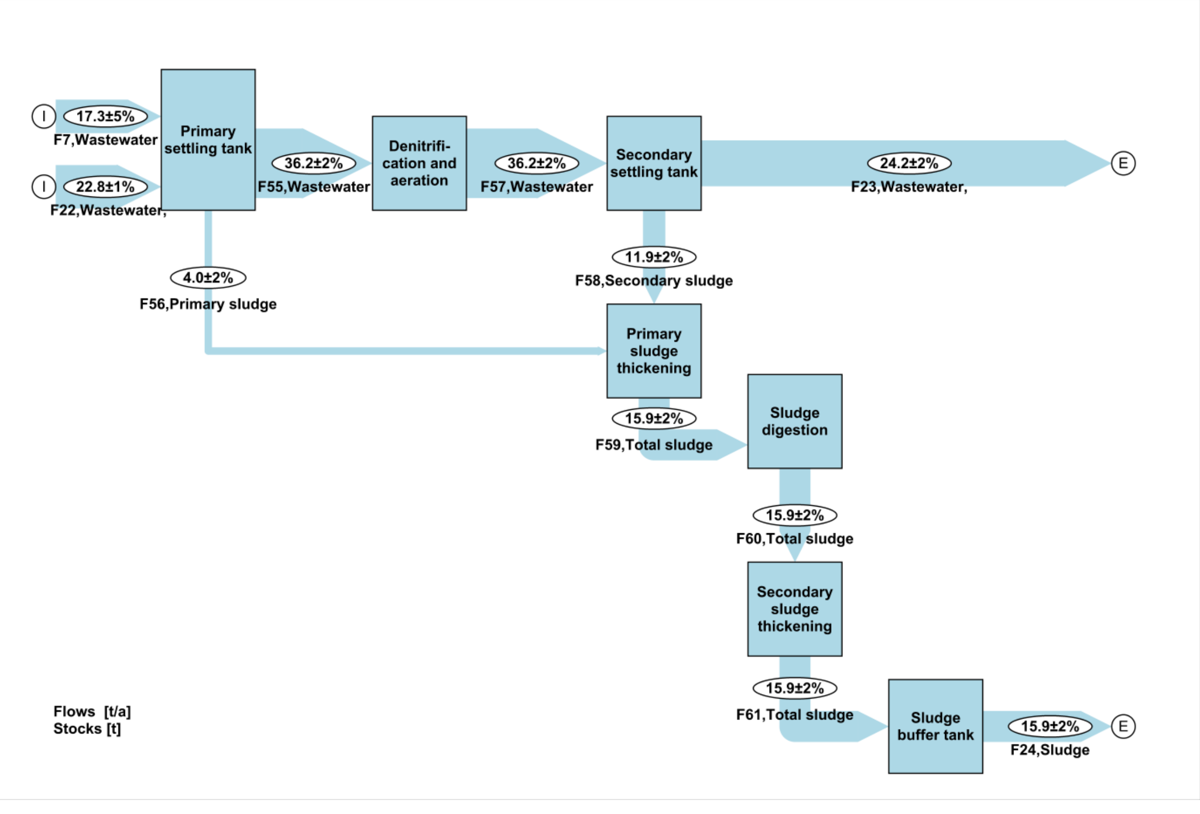

Figure 6-4: SFA of wastewater treatment plant (WWTP) in Renkum, the Netherlands.

[72] This chemical ensures coagulation of non-settleable, often colloidal substances. After coagulation, these non-settleable particles can be formed into larger 'flocs' (referred to as flocculation) which allows sedimentation (settlement) of the particles (Gao et al., 2002).

[73] This calculation is made by taking the removal efficiency of the WWTP and multiplying this ratio (0.43) with the total P influent from Wageningen.

6.2.2.3. Specific findings P output: Municipal solid waste:

Households

It is estimated that households in Wageningen annually produce approximately 2396 t of food waste that ends up in the MSW stream. This equals around 5.5 t P/yr (For methods and sources used for calculation of flows, see Appendix I: Data collection per subsector of P output), of which most ends up of in the mixed waste (see Figure 6-5).

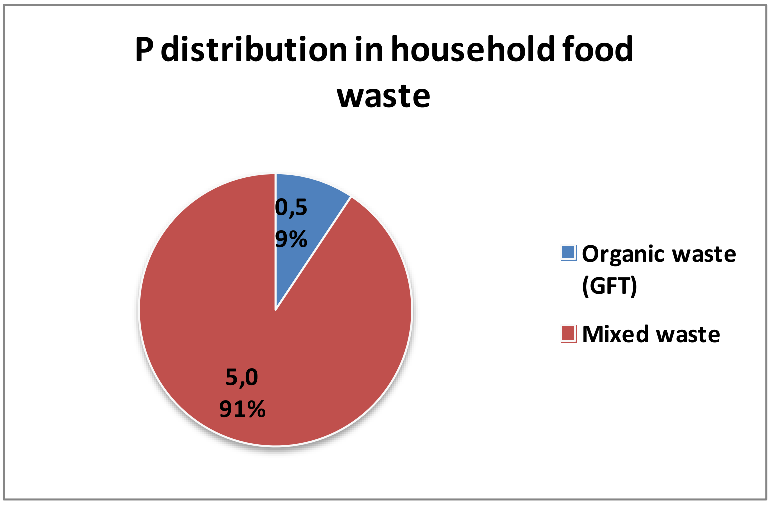

Figure 6-5: Division of P in household food waste in Wageningen, in t/yr and percentage. See Appendix I: Data collection per subsector of P output, for method of calculation

According to sorting analyses in household waste performed by the municipality itself, food waste from households is partly separated and disposed via the organic waste stream, but mostly[74] ends up in the mixed waste stream (Gemeente Wageningen, 2012a). This finding is also supported by the Dutch study conducted by Van Westerhoven and Steenhuisen (2010) on destination of household food waste, which was used as a basis to calculate the food waste and their destination. The authors state that 78 % of total food waste ends up in the mixed waste. In addition to disposal of food waste via the MSW route, home-composting is also practiced in approximately 150 households (Gemeente Wageningen, 2012a). This practice however, concerns only a very minimal amount of P (3.6 *kg* P/y), basically a negligible flow (<F18>) as shown in the SFA of households below.

[74] No exact fractions of food waste in mixed waste were published (Gemeente Wageningen, 2012a)

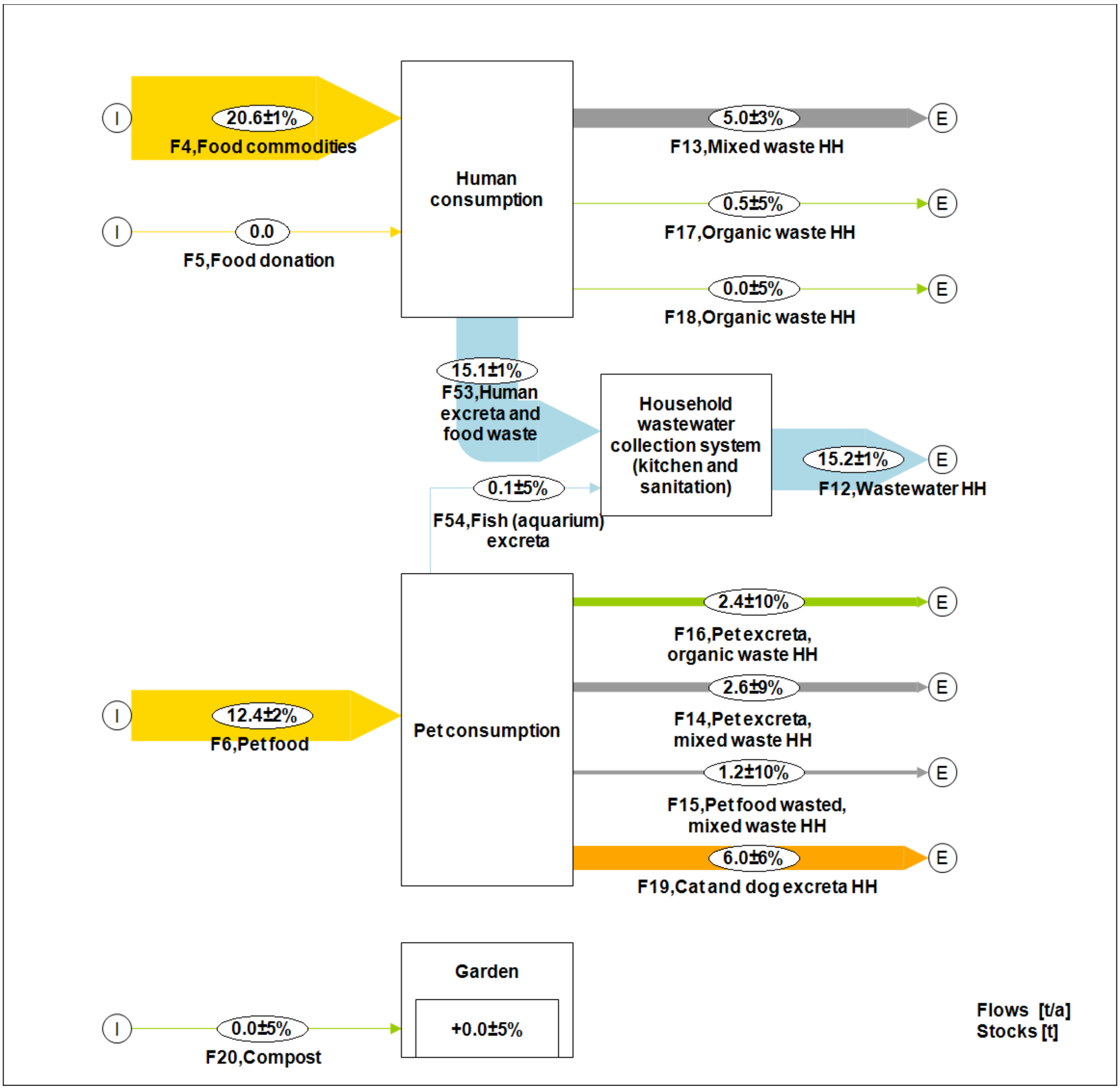

Figure 6-6: SFA of P in t/yr through households, Wageningen, the Netherlands, 2012

Besides food waste, also P related to pet consumption is found in the household waste flow. Results show this to be an important flow, as it represents 25 % of the total P input of households (12.4 t P/yr), demonstrated in Figure 6-7. The calculations are based on the dietary P intake of pets (Kirsimaa and van Dijk, 2013) and also includes the fraction of pet food assumed to be wasted (Kalmykova et al., 2012). For more information on how calculations were made see Appendix I: Data collection per subsector of P output. Of this total P input, the largest fraction is ascribed to dogs (over 6 t P/yr), then cats (2.4 t P/yr) and an almost equal flow to pond fish (2.2 t P/yr). Although the P consumption for a pond fish is not very high (0.08 *kg* P/y), pond fish are by far the largest group of pets represented in the Netherlands (Borst et al., 2011).

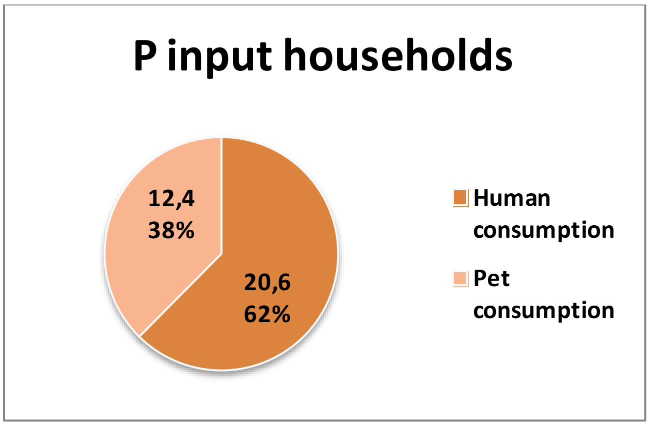

Figure 6-7: P input related to human consumption and pet consumption for households in Wageningen, in t/yr and percentage. See Appendix I: Data collection per subsector of P output, for methods of calculations.

The pathway of P found in the waste stream related to pet consumption, proved more difficult to assess. Based on a combination of literature, reports, and contextual assumptions with regard to the average Dutch person and Wageningen, the following is supposed:

Wasted pet food is presumed to be disposed of in the mixed waste out of convenience, as it is often contained in packaging that is not allowed in the organic waste container. Furthermore, it is estimated that a large part of cat and dog excreta (and the associated P) ends up on land (see Figure 6-6). Due to lack of precise data, for dogs it is presumed that all urine is discharged on land and most likely a large part of the faeces is not cleaned up (there is a lot of nature around Wageningen where dogs can walk freely). Therefore, the rough assumption is made that 70 % of total P excreted by dogs ends up on land. For cats, research estimates that 75 % of cat excreta ends up in public space (Wageningen UR Livestock Research, 2011). As it is difficult to determine how much of this is urine or faeces, for simplification, it is assumed that 75 % of total P excreted by cats ends up on land. This excreta ending up on land is a diffuse flow that is accumulated and therefore represented as a stock in the SFA. It is however currently marked as 'lost' from the perspective of this thesis, since the P is not reused or recycled back into the human food system. The remaining P from cat and dog excreta is supposed to be disposed of in the mixed waste stream for hygienic reasons (Milieu Centraal, 2014). In Wageningen, it is officially mandatory for dog poo to be disposed in 'dog bins'. It is thus assumed the remaining 30 % of P in dog excreta ends up in these bins and is treated as mixed waste (Gemeente Wageningen, 2013d). With regard to cats, it is estimated that the remainder of 25 % of P ends up in mixed waste via disposal of the kitty litter box, because it is not expected that many people buy environmentally friendly 'kitty litter coming' that allows disposal in the organic waste stream. The excreta of small pets (comprising of rabbits, reptiles, rodents, birds and carrier pigeons) is assumed to partly end up in the organic waste, as the excreta from small pets is allowed in the organic waste container (Gemeente Wageningen, 2012c). However, it is assumed that not all inhabitants do this (all the time) and therefore, it is assumed that half is destined for the organic waste stream and the other half ends up in mixed waste. The excreta from pond fish are presumed to end up in the organic waste stream. This is based on the expectation that captured organic matter (including the poo), due to cleaning of ponds to avoid algae growth, is mainly disposed of in the organic waste container[75]. Excreta from aquarium fish is assumed to be discharged through the sink (addressed previously in section 6.2.2.2 concerning wastewater).

The destination of P disposed of in the organic waste stream (totalling 11.7 t P/yr) is as follows: On arrival at Twence it is first anaerobically digested. During anaerobic digestion, biogas is produced, but all P remains in the sludge (Malakahmad et al., 2013). According to Schievano et al. (2011), who researched continuous stirred-tank reactors (CSTR), 2-9 % of P can be retained in the reactor, due to sorption on small particle surfaces. However, the technology used for anaerobic digestion at Twence (which processes the largest amount of organic waste) is a plug flow reactor, also known as DRANCO (DRy ANaerobic COmposting) (Twence, 2008; Wierinck, 2010). Here, no sedimentation is said to take place (Wierinck, 2010). Although sludge is recirculated back into the system, all initial input eventually leaves the system as digestate. Therefore, it is assumed that for all P destined for anaerobic digestion: input equals output. Thereafter, it enters the composting process. A regular composting process also produces leachate, which contains part of total P (Pognani et al., 2012). However, at Twence the composting process is engineered and controlled in tunnels (vessel composting). Here the liquid is recirculated in the process of composting. This results in the P remaining in the compost and water being evaporated. Therefore, any P leaching from the composting process is found insignificant (Wim de Jong, personal communication, December 19, 2013).

Apart from engineered composting, some of the organic waste is home-composted as explained earlier. According to a study conducted Andersen et al. (2011), the loss of nutrients (studies limited to P and K) from home-composting is very low. Most of the nutrients are found in the compost itself. As the compost is in tanks and therefore not exposed to rainfall (which could result in P in formed leachate) a minimal loss of 1 % is assumed. As the initial amount of P destined for home-composting is already negligible, the flow of compost returning to land and leachate formed in the process of composting are very insignificant. Nevertheless, it is taken up in the SFA (see Figure 6-6) to demonstrate the possible pathways of P through Wageningen.

The mixed waste containing organic waste rich in P is assumed to be incinerated. Furthermore, it is assumed that all P, after incineration, ends up in ash (bottom or fly ash) (Godbout et al., 2012; Zhang et al., 2001). The Netherlands has strict regulations on reuse of such ashes to avoid landfilling (VROM, 2013). According to Lamers (2010), the utilization grade of such ashes in the Netherlands was 100 % in 2010. These ashes are used for different types of infrastructure. Usually it's employed for elevation of embankments, but also in asphalt or concrete (Rijkswaterstaat Leefomgeving/Bodem+, 2014). As such, the ashes are used, but the P is 'lost'.

Non-households

As explained in the section 3.3.1, accurate data collection for the non-household sector proved very challenging. The estimated P flow quantities and its pathway through the system is often based on many assumptions and rough calculations. Below the SFA of non-households (Figure 6-8) is first presented to gain an overview of P flows (together amounting to 10.6 t P/yr). Thereafter the findings are described in depth per subsector.

[75] Organic matter from cleaning of ponds is called 'slootmaaisel' and is considered organic waste (Schoonenberg, 2010)

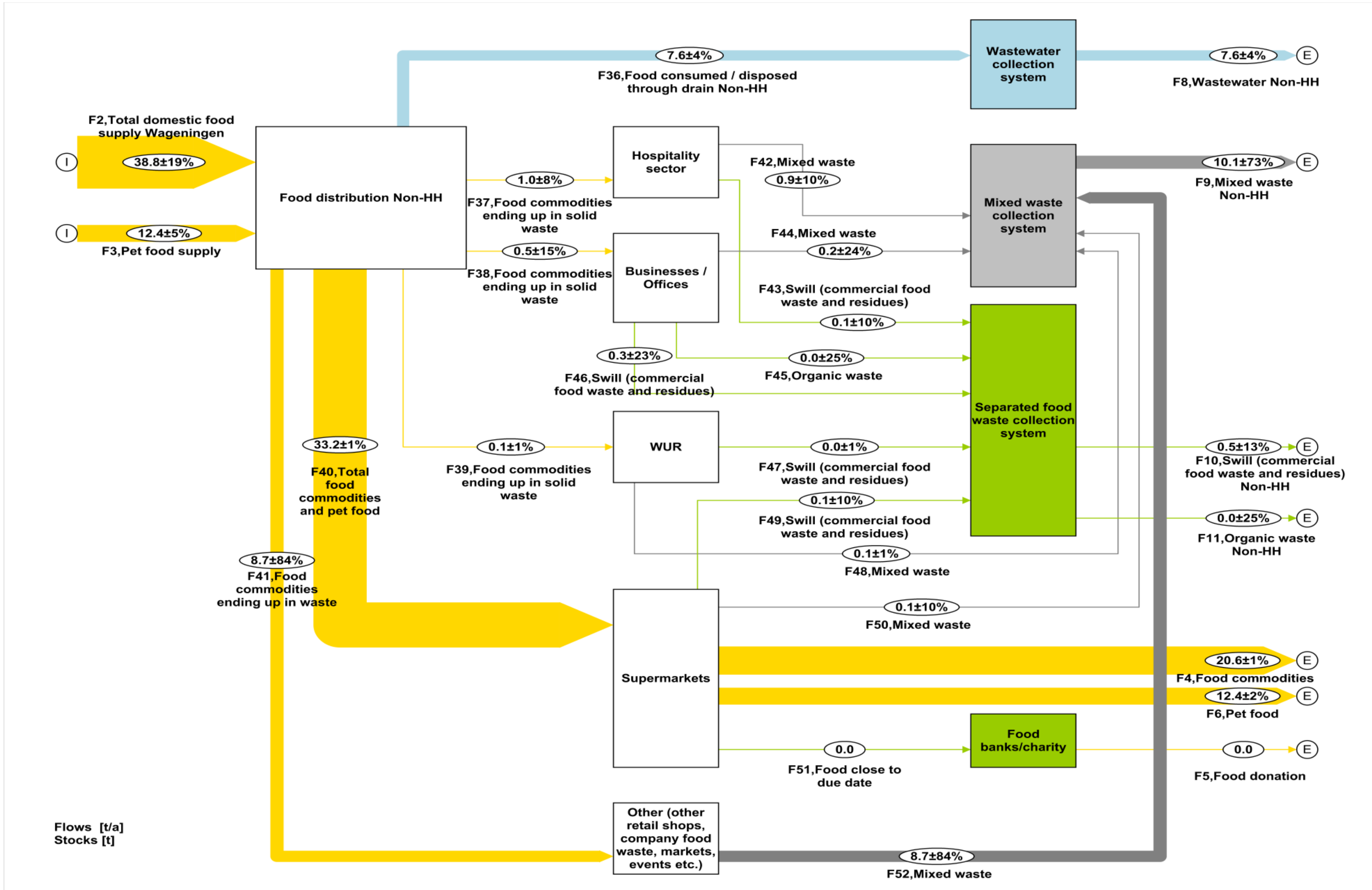

Figure 6-8: SFA of P in t/yr through the non-household sector, Wageningen, the Netherlands, 2012

WUR

Due to accurate waste collection data received from the WUR, the amount of food waste and its disposal method could be fairly accurately assessed. In addition, Dutch research was conducted on the amount and composition of food waste from catering services at a Dutch university (van Westerhoven and Steenhuisen, 2010). This source allowed for calculation of food waste composition and thus the amount of P showing to be about 0.1 t P/yr. Of this amount, most is sent to mixed waste (0.1 t P/yr), because only Forum (Orion was not built at the time of the base year of 2012) had a separate organic waste collection system that was monitored by the company EcoSmart. It was not found feasible to implement this at every WUR building (less canteen and catering waste). The food waste separated at source (only 0.008 t P/yr) is treated as swill. Swill is sent to anaerobic digestion by the waste collection and treatment company Van Gansewinkel, according to Monique Groen, Occupational Health and Safety, and Environmental expert at the department of Facility Management, Wageningen UR (personal communication, October 25, 2013). The mixed waste is incinerated, and although some food waste is separated, the sludge produced from anaerobic digestion is also incinerated (Maarten Duineveld, personal communication, November 22, 2013). The destination of P containing ashes after incineration is already addressed earlier in the previous subchapter of 'Households'.

Hospitality sector

The largest food related P flows within the non-household sector (with exception of category 'Other') are assigned to the hospitality sector: slightly over 1 t P/yr. Although much of the core business of the hospitality sector concerns preparing and selling of food, little of the food waste is separated at source.

Restaurants for example, according to a UK study by WRAP (2013a), a UK research institute focusing on the topic of sustainable resource use, are said not to practice recycling of food waste. Quick Service Restaurants (QSRs) on the other hand, score the highest in separating food waste: 33 % of total weight of food waste is destined for anaerobic digestion (WRAP, 2013a). This finding is also confirmed in a Dutch study on food waste in restaurants, conducted by research and consultancy company CREM (2010). Here, it is found that the investigated restaurant does not have very good recycling practices. This is in contrast to fast food chains which appear to be much more efficient in handling waste. In total, the hospitality sector only separates food waste representing 0.1 t P/yr, which is treated as 'swill' and ends up being anaerobically digested (CREM, 2010; WRAP, 2013a). No distinct information could be found of the eventual destination of produced digestate containing P. Therefore it is assumed that all P is destined for energy recovery through incineration[76]. The P containing ashes are used in road works and infrastructure (already addressed earlier in this chapter, see 'Households').

[76] Due to lack of data and knowledge on specific waste handling routes, the assumption is based on personal communication with Maarten Duineveld, key account manager at Van Gansewinkel. Van Gansewinkel collects the swill from WUR (Monique Groen, personal communication, October 25, 2013) and is one of the other waste handlers of company waste known to be active in Wageningen (Anja Spee, personal communication, November 15, 2013). He explains that digestate at Van Gansewinkel is incinerated (Maarten Duineveld, personal communication, November 22. 2013).

Supermarkets

Besides food commodities and pet food products sold to households in Wageningen, supermarkets also deal with food losses from products that cannot be sold. The total amount of food waste from supermarkets in Wageningen amounts to 9.3 t/yr. Priority food waste categories that require most attention are fruit, vegetables and bread (Stenmarck et al., 2011; Tesco, 2013). In the total amount of food waste, it is estimated that 0.2 t P/yr is present.

The disposal method of supermarket food waste (and thus of P) in the Netherlands is difficult to assess, since specific data is not made available (Hilke Bos-Brouwers, personal communication, October 11, 2013). Stenmarck et al. (2011) found that the actual management of supermarket food waste in a Norwegian study was unknown, but disposal methods are known to be either donation to charity, fermentation (anaerobic digestion), animal feed or mixed waste. Animal feed was not taken into consideration, as it is mentioned by WRAP (2013b) that food waste used as an ingredient in animal feed all originates from manufacturing sector and not from 'supermarkets'. This leaves donation, anaerobic digestion and mixed waste as disposal methods. These disposal methods are assumed to be applicable in the Netherlands, since the Responsible Retailing Report of Ahold (Koninklijke Ahold N.V., 2013) that also concerns figures on Albert Heijn, a large supermarket chain in the Netherlands, mentions fermentation in its figures as well as donation (Koninklijke Ahold N.V., 2013).

Of total food waste it is assumed 0.5 % is donated to charity, e.g. food banks. This estimation is based on another report by WRAP (WRAP, 2013b): "Estimates of waste in the food and drink supply chain". Although the calculated percentage of food waste donated based on this report is only around 0.1 %, it is rounded off towards 0.5 % for ease of calculation. With regard to anaerobic digestion, the assumption is made that 30 % of food waste is fermented. Stenmarck et al. (2011) mention that Sweden formulated the national objective for 2010 of sending 35 % of all food waste for anaerobic digestion (Avfall Sverige, 2009). Stenmarck et al. (2011) simultaneously mention this had not yet been achieved in 2011, due to much food being packaged, which is labour intensive to sort and separate. This targeted 35 % in Sweden is assumed to be somewhat too high for the Netherlands, since Sweden is considered a frontrunner on environmental policy and measures (OECD, 2004; Swedish Institute, 2014). Especially, since a WRAP study (2013a) on the UK reports a very low percentage of food waste sent to anaerobic digestion, not even 5 % is *sure* to be anaerobically digested (AD). However, the same report also states that is percentage can be on the low side, as the other category is 'unknown'. This entails that part of food and drink waste that is ascribed to category 'unknown' might in fact be anaerobically digested, but this cannot be stated with certainty (WRAP, 2013b). Therefore, the fairly optimistic estimation of 30 % of food waste (labelled as 'swill' waste stream) is diverted to anaerobic digestion. This means that the largest part, 69.5 % of food waste from supermarkets, ends up in mixed waste. These percentages are subsequently applied to the calculated P flow in supermarket food waste. Again, no distinct information could be found of the eventual destination of produced sludge containing P. Therefore it is assumed that all P in sludge is incinerated[77]. The destination of P in incineration is already addressed earlier in this chapter (see 'Households').

Businesses/Offices

The amount of P in food waste from company catering services and from people bringing their lunch in businesses and offices (BO) in Wageningen is estimated at 0.5 t P/yr. The pathway of P was difficult to identify. The municipal waste collector, ACV group, also collects company waste. Out of 249 BO where waste is collected, six (2 %) also contracted separate organic waste collection (GFT) and 135 (54 %) are estimated to have separate swill collection. These percentages per disposal route are applied to P found in food waste from company catering, as it also corresponds with findings in a WRAP report on food waste disposal in the staff catering sector (WRAP, 2013a)[78]. No exact information is provided on the waste treatment process of separately collected organic waste from businesses in Wageningen. At Van Gansewinkel, a waste processing company that also collects company waste in Wageningen, GFT is composted (Maarten Duineveld, personal communication, November 22, 2013). Therefore, it is assumed all organic waste collected from businesses is directly composted and thus reused. With regard to collected swill the following is assumed: The P in the produced digestate that originates from companies where ACV is responsible for swill collection, is sent as fertiliser to Germany (ReFood, 2014)[79]. For the remaining companies that are estimated to separately collect swill, all P is presumed to eventually be incinerated (Maarten Duineveld, personal communication, November 22, 2013).

Other

The mass balance principle of SFA methodology dictates that all input needs to be accounted for in either an output, or a stock in the system. The difference between the calculated P input and calculated P output results in a residual flow of P. This residual flow is expected, since not all food-selling sectors are accounted for in this thesis (see section 3.3). This residual flow (<F41>) amounts to approximately 7.7 t P/yr. The reason for the residual flow to be ascribed to MSW from the non-household sector is due to the uncertainty of data being the highest in this particular sector (also addressed in section 7.2, 7.5.2 and Appendix III: Uncertainty of flows). It is presumed this might be food waste from other retail shops (besides supermarkets), food waste occurring during lunch at companies without professional catering, catering for specific events throughout the year, markets or vending machines. Due to a lack of knowledge and the notion that most of food waste ends up in mixed waste (see van Westerhoven and Steenhuisen, 2010), this is also presumed for the residual flow.

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[77] Due to lack of data and knowledge on specific waste handling routes, the assumption is based on personal communication with Maarten Duineveld, key account manager at Van Gansewinkel. Van Gansewinkel collects the swill from WUR (Monique Groen, personal communication, October 25, 2013) and is one of the other waste handlers of company waste known to be active in Wageningen (Anja Spee, personal communication, November 15, 2013). He explains that digestate at Van Gansewinkel is incinerated (Maarten Duineveld, personal communication, November 22, 2013).

[78] Here, also 54 % of food waste is approximated for anaerobic digestion (WRAP, 2013a) – although this also includes food waste disposed through the sink that is not taken into account in this study.

[79] According to Marga van het Erve (personal communication, December 12, 2013), the collection of swill is contracted by ACV to ReFood and Rotie. ReFood publishes on its website the digestate is used for making DynAgro (a fertiliser), which is send to Germany (ReFood, 2014). The exact process is unknown. For simplification, this destination is assumed for all swill collected through ACV from companies with company catering.

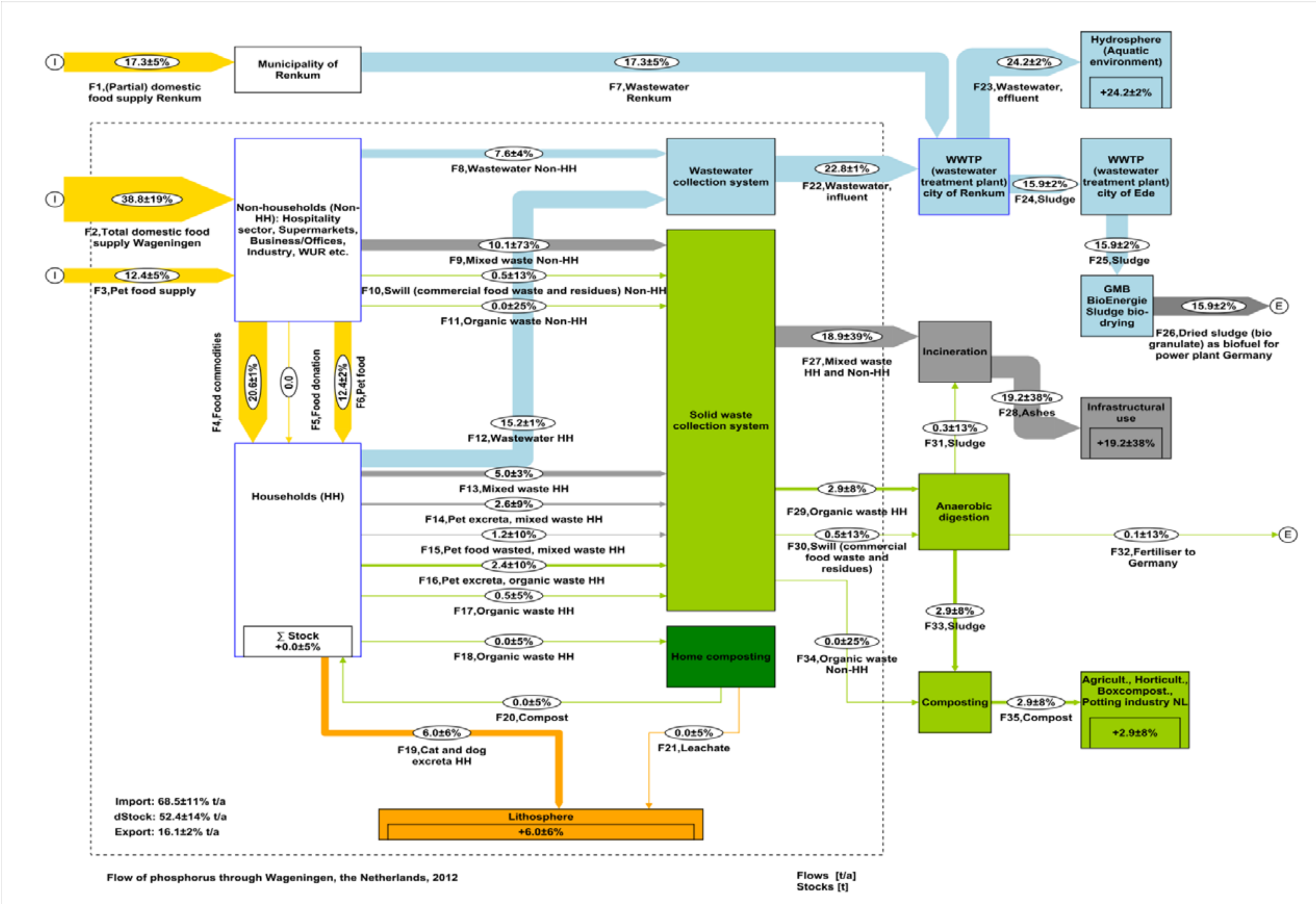


Figure 6-9: SFA of P in t/yr, Wageningen, the Netherlands, 2012

6.2.2.4. Overall findings

The SFA shown on the previous page (Figure 6-9) shows a comprehensive picture of the overall performance of Wageningen with regard to P use.

Here, certain flows clearly stand out. It can be noticed that most of the P input is directed towards households (<F4, F5>), which is approx. 33 t P/yr, which accounts for 64 % of the total P input. Not all P input could be accounted for by calculations on the P output per (sub)sector. This residual flow (<F41>) is relatively large, since it accounts 15 % of total P input. The size of this flow is however considered very uncertain and is discussed more in depth in section 7.2 and 7.5.2.

With regard to the P output, the WWTP receives most of the total P (<F22>). Yet, it must be noted that calculations in this study show that in the case of Wageningen, MSW treatment plants receive an almost equal fraction of the total P input (Figure 6-8). This finding illustrates the equal importance of both MSW and WW with regard to reuse and recycling of P.

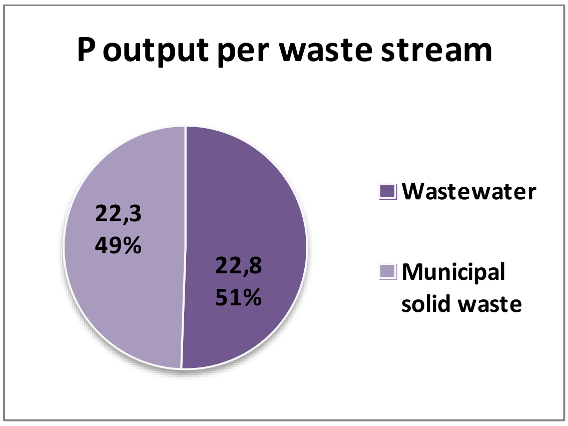
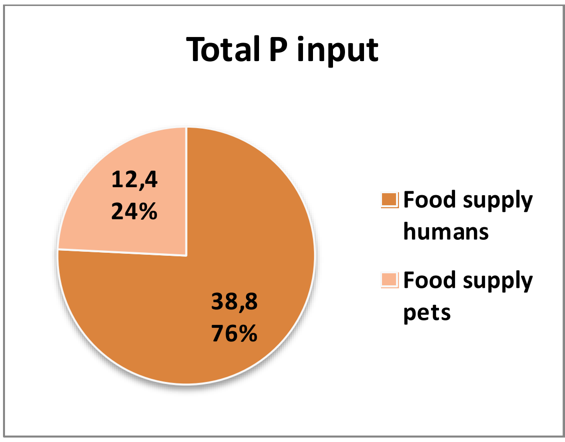


Figure 6-10: Division of P output per waste stream in t/yr and percentage, Wageningen, the Netherlands.

Other remarkable flows are related to pet consumption. It appears pet food is responsible for a relatively large part of the *total* P input flow in Wageningen (<F3>), which is illustrated in the pie diagram below (Figure 6-11). It is interesting to note that pets are also responsible for the largest part of total P reuse taking place in Wageningen (Figure 6-12).



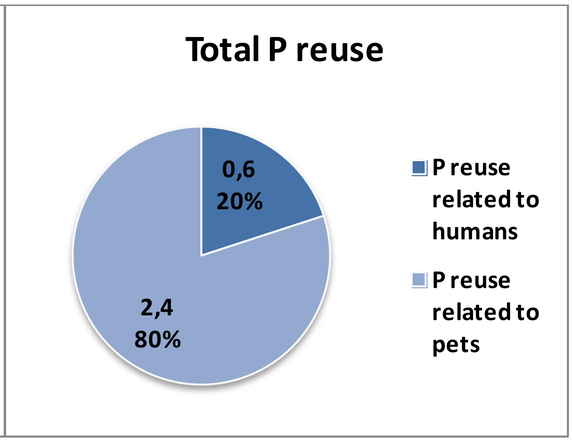


Figure 6-11: Total P input of human and pet related consumption in t/yr and percentage, Wageningen, the Netherlands.

Figure 6-12: Total P reuse of human and pet related consumption in t/yr and percentage, Wageningen, the Netherlands.

What also becomes clear through the SFA is that most of the P input in Wageningen is eventually 'lost' (94 % as shown in Figure 6-13). There is no P recycling and only a small amount of P is reused – mostly in the form of compost (<F35>).

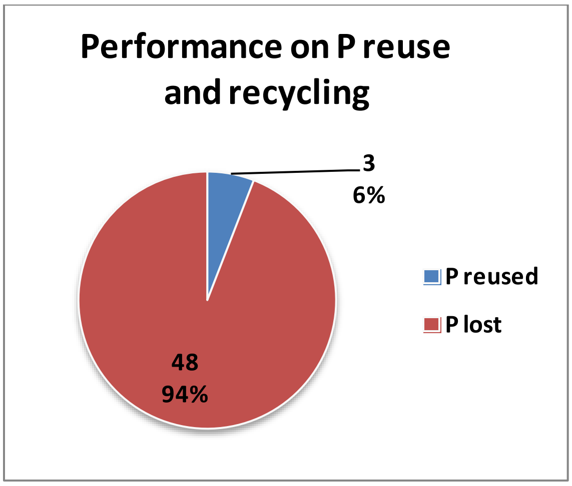


Figure 6-13: Performance on P reuse and recycling in t/yr and percentage, Wageningen, the Netherlands.

There is no P recovery and recycling from WW in the form of struvite, because all P in WW is lost: partly through discharge on the river Rhine (<F23>) and partly through incineration as the sludge serves as biofuel (<F26>). Apart from cat and dog excreta ending up on land, the remaining P input from food related flows is disposed of in MSW. Both the households (9.1 t P/yr) and non-household sector (0.4 t P/yr)[80] contribute to the *reuse* of P in the form of compost and fertiliser (<F32, F35>). Despite these efforts, it clearly shows that this amount is minimal, compared to the amount of P incinerated and ending up in road works and infrastructure (<F28>).

Finally, there are also some flows that have been considered and calculated for sake of exhaustiveness, yet actually appeared to have little to no impact. Prime examples of this are organic waste from households (<F18>) destined for home-composting, the amount of food donated from supermarkets (<F15>), and separate collection of organic waste (GFT) from BO (<F11>).

[80] This number has a high level of uncertainty. For more information see Appendix III: Uncertainty of flows. In section 7.5.2, this is further discussed in depth.

6.3. Alternative strategies

From results on the current situation (section 6.2) it appears that the performance of P reuse and recycling in Wageningen is fairly poor (only 6 % of total P input). In this subchapter potential alternative strategies on the level of physical infrastructure to improve this performance, are explored. In doing so, a distinct division is made between WW and MSW.

Per waste stream, first an overview is given of current developments in two parts. Similar to the workings of a funnel, first attention is paid to developments outside (*external)* of Wageningen: In what background is the municipality operating and what are options known from other pilot projects (with a focus on the Netherlands)? From there, the scope of options is narrowed by paying attention to developments within *(internal)* the municipality, its future plans and limits. This provides an understanding of how the choice for certain strategies came about. Immediately thereafter, the proposed strategy is introduced and further explained. Finally, the proposed strategies are calculated and the effect on the performance of Wageningen is addressed.

6.3.1. Wastewater: current developments

6.3.1.1. External developments

National context

In the Netherlands, there is an ongoing development in WW management from merely removal of P, towards actual recovery and recycling of P. The eutrophication issues in the Netherlands explained in section 4.4, has led to legal restrictions on the amount of P in the effluent (Baas and de Zeeuw, 2010). This made removal of P from WW necessary in the Netherlands, but did not specifically stimulate recovery and recycling of P. The need for P removal led WWTP to opt for the use of chemicals (such as $AlCl_3$ of $FeCl_3$) to chemically bind P and have it retain in the sludge, or use of biological removal of P through so-called 'phosphate accumulating organisms' (Bio-P) (Rittmann et al., 2011; STOWA, 2001).

Moving from merely removal of P to actual recovery and recycling at WWTPs, mostly has to do with preventing clogging of pipes and enhanced dewatering of sludge (STOWA, 2012; van Roekel, 2013; Martin Wilschut, personal communication, October 25, 2013; Jan Weijma, personal communication, October 30, 2013). If Bio-P is chosen for P removal, there is natural struvite precipitation taking place in the sludge treatment process. Struvite, or magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4.6H_2O$) is a white powdery, crystalline substance (see Figure 6-14).

Figure 6-14: Struvite. Source: Adopted from Waternet, 2014.

Struvite in itself is a valuable product, as it suited for agricultural purposes and can be used as a slow-release fertiliser (Kujawa-Roeleveld and Zeeman, 2006; van Velzen et al., 2013). However, when the struvite precipitation process is not controlled, the natural formation of struvite clogs pipes (STOWA, 2012; van Roekel, 2013). Although this can easily be avoided when using the afore-mentioned chemicals (this also binds P and avoids clogging of pipes), high chemical use is not desired. This increases the amount of salts in the effluent and also produces more sludge (STOWA, 2012). Another advantage of controlled struvite precipitation is that WW sludge is somehow more easily dewatered when it contains less P according to Van Roekel (2013) and Jan Weijma, Business developer at LeAF and researcher at Wageningen University (personal communication, October 30, 2013). Less volume means lower transport costs to have sludge further processed at companies like GMB BioEnergie. A recent and prime example where P recovery and recycling in the form of struvite is now taking place is the WWTP in Amsterdam[81] (STOWA, 2012; van Roekel, 2013).

The increased concern on the topic of (economic) P scarcity and geopolitical dependency is also a stimulus for current initiatives on recovery and recycling of P, but it is clearly not the main driver (STOWA, 2012; van Roekel, 2013; Martin Wilschut, personal communication, October 25, 2013; Jan Weijma, personal communication, October 30, 2013). At present, the domestic market with manure - and thus a P surplus - has no demand for such a product as struvite. The Dutch Fertiliser Act still prevents use of struvite as fertiliser in agriculture, which makes export necessary. This is due to the origin of struvite being a waste stream (Ehlert et al., 2013; van Velzen et al., 2013; Wouter de Buck, personal communication, October 18, 2013). The regulations prohibit the use of waste streams as a fertiliser. Exceptions are possible if the imposed requirements are met, but currently struvite is not mentioned in this law. However, struvite is recently advised by experts to take up in the Dutch Fertiliser Act under certain conditions of purity (avoiding risks of pathogens, heavy metals etc.) (Ehlert et al., 2013)[82]. Therefore, its use as a fertiliser in agriculture is expected to become legal in the near future. Despite efforts for such legalisation, it is not expected there will be an actual demand for the product within the Netherlands, due to the large amounts of manure present and P surplus (see section 4.4.2). Economically, struvite also poses a challenge, since its production costs more than its present market price: struvite is only worth around 50 € per tonne (Martin Wilschut, personal communication, October 25, 2013; van Velzen et al., 2013). Therefore, at the moment it cannot sufficiently compete with conventional fertilisers, such as diammonium phosphate and superphosphate (Balmér, 2004; Rittmann et al., 2011; Martin Wilschut, personal communication, October 25, 2013; Marco de Mik[83], personal communication, November 8, 2013).

Apart from alterations at the current 'centralised' WWTPs, also alternative, Decentralised Sanitation and Reuse systems (DESAR) are being researched in the Netherlands (Everard, 2013). Here, various WW streams are separated at source (building level) and (partially) treated on site or nearby (Figure 6-13). The waste streams can be distinguished into black water (urine, faeces and potentially kitchen waste), grey water (from kitchen, shower, sinks etc.), and rain water (Zeeman et al., 2008).

[81] For more information on technology implemented in Amsterdam, see the report by STOWA (2012)

[82] For more information on this advice and the proposed conditions under which to accept struvite as a fertiliser, please consult Ehlert et al. (2013)

[83] Nutritionist at Agruniek Rijnvallei, an animal feed company located in Wageningen, the Netherlands

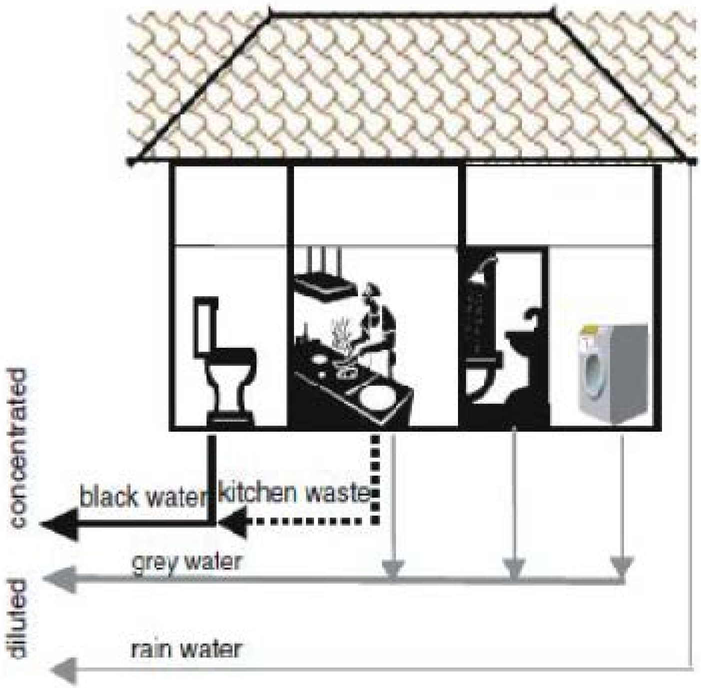


Figure 6-15: Source separation of waste streams at household level. Source: Adopted from Zeeman et al., 2008.

DESAR results in concentrated waste streams that allow for more efficient and cost-effective recovery of P and nutrients in general, but also removal of micro-pollutants (Kujawa-Roeleveld and Zeeman, 2006; Martin Wilschut, personal communication, October, 25, 2013). Micro-pollutants refer to pharmaceuticals, hormones, detergents and other personal care products, of which their impact on water bodies has become an increasing topic of concern (Everard, 2013; Harder, 2012; Maurer et al., 2006; van Velzen et al., 2013). In addition, DESAR concepts are interesting due to its potential for energy recovery from black water (biogas) and efficient water (re)use (minimal water use in vacuum toilets[84] and grey water/rain water reuse). With the agreement signed between the Dutch Ministry of Infrastructure and Environment, the water boards and all municipalities to reduce costs related to the water chain in 2020 by € 380 million euros per year, DESAR concepts present an interesting alternative (Dutch Ministry of Infrastructure and Environment, 2011; Harry Post, personal communication, October 30, 2013).

DESAR concepts are also interesting from the viewpoint of the municipality, because centralised WWTPs are beyond its influence (they fall under the responsibility of the water boards). DESAR concepts however, can be applied on a more local/regional scale in which the municipality could be more an active party involved in P recovery and recycling. Examples of some DESAR pilot projects taking place in the Netherlands are thus addressed in 'Possibilities and pilot projects' further below.

[84] Where a regular flush toilet is said to use approximately is 5.9 compared to only 0.5-2 L per flush for a vacuum toilet (Foekema et al., 2007; Mels et al., 2005).

Regional context

Apart from national developments with regard to P recovery and recycling, attention also needs to be paid to specific future plans of the WWTP in Renkum. Having one central point of treatment where practically all WW ends up (different from MSW), makes the future plans of the water board 'Vallei en Veluwe' for the WWTP in Renkum of particular interest. After all, plans for P recovery and reuse on the WWTP would affect the need for, and type of strategy, deployed in Wageningen.

At present the WWTP is not suited for P recovery and recycling. As explained in 6.1.1, the use of AlCl3 (aluminum chloride) binds P – making its recovery in the form of struvite difficult to impossible. In addition, there is no sludge dewatering facility at the WWTP. With the sludge being diluted with water, it is not a sufficient concentrated stream of nutrients that allow for economically feasible recovery of nutrients (Rinus van der Molen, personal communication, March 13, 2014). Furthermore, no relevant future investments are going to take place that might provide a window of opportunity to implement P recovery and recycling. Seeing as the recovery and recycling of P in the Netherlands is not demand driven, it does not seem likely this is implemented at the WWTP in Renkum within the coming years. Despite these limits, several future scenarios are possible. There might be two possible developments in future, external to the WWTP, which would result in P reuse or recovery and recycling:

1) Stricter legislation formulated by the national government (Rijkswaterstaat) on P discharge to 'national' waters such as the Rhine
2) Extraction of P found in treated WW sludge, or return of P found in treated WW sludge to agriculture in the form of a safe and neutralised product [85]

Both of these developments are not expected to take place in the near future. No indication for stricter standards is known and the sustainable application of WW sludge is only in a research phase.

An option on the local scale of the WWTP is collaboration with the neighbouring paper factory Norske Skog Parenco (shortened as Parenco), that has its own WWTP. Collaboration would be interesting for both parties as it could lead to an increase in sustainability performance, lowering of costs and optimal use of residues arising from the process. There have been plans for some time, to combine (parts) of both WW treatment processes. For example, combined digestion of sludge is interesting, as it could allow for the production of more energy through forming of biogas (van der Molen, 2012). Moreover, such collaboration would eliminate current transportation costs to the WWTP in Ede for dewatering of sludge, because Parenco has dewatering facilities. At present, after dewatering its sludge, Parenco incinerates its dried sludge for energy recovery to fuel its production process (Rinus van der Molen, personal communication, October 16, 2013). This means P in WW would still be lost *if* the focus is limited to energy recovery only (through biogas, incineration and cutting of transport costs) and nutrients are not sufficiently considered (Rinus van der Molen, personal communication, October 16, 2013; van der Molen, 2012). It is also possible that

[85] Martin Wilschut (personal communication, October 25, 2013), responsible for technology innovation and development at GMB BioEnergie (the company currently contracted to process sludge from the water board Vallei en Veluwe) explains that at present, opportunities for use of the biogranulate in agriculture, is researched. This indicates that in the future, P in sludge might potentially be either reused or first recovered and then recycled. According to Van der Molen (2012), water cycle advisor at water board 'Vallei en Veluwe', the water board aims to take sustainable criteria into account with regard to the processing of sludge (nutrient and energy recovery) with all future contracts.

developments in the paper and cardboard market, lead Parenco to make investments in its production lines. Upgrading production would also require an upgrade and renewal of its WWTP. When combining efforts for investment with the water board, then simultaneously P recovery and recycling techniques could be implemented in the process of renewal of (both) WWTPs (Rinus van der Molen, personal communication, March 13, 2014).

Either way, Rinus van der Molen (personal communication, March 13, 2014) explains that any form of collaboration is mostly dependent on the capacity and willingness of Parenco to make investments for combining both WW treatment processes. With the current plans having a focus on energy, the dependence on Parenco and developments in the paper market, as well as the potential (health) issues[86] with combining communal WW and industrial WW, make it unlikely that such a large scale transition is going to take place in the very near future. Without P recovery and recycling on the WWTP, it would be up to the municipality of Wageningen to implement more decentralised sanitation options that divert some of the WW for subsequent P recovery and recycling. Some of these options are outlined below.

Possibilities and pilot projects

In the Netherlands, several alternative sanitation and WW treatment pilot projects are taking place. With regard to P recovery and recycling the most interesting possibilities for the municipality of Wageningen are found to be as follows:

1) Separate urine collection (limited to events)
2) Separate black water collection connected to a decentralised treatment (DESAR). Potentially combined with kitchen grinder for kitchen waste collection

In general, separate urine collection, is an interesting opportunity from the perspective of P recovery and recycling. Of total P excreted by humans, 60-70 % is found in urine (Cordell et al., 2011; Schröder et al., 2010). Moreover, it represents approximately 50 % of total P found in communal WW, whilst in volume, urine is only 1 %. Diverting urine results in a concentrated stream of P, allowing for efficient P recovery and recycling (Kalmykova et al., 2012; Mels et al., 2005). Although urine can be fairly easily sanitised through storage and applied on agricultural land (Kalmykova et al., 2012; Kujawa-Roeleveld and Zeeman, 2006), this option is not considered in this thesis due to legislative barriers that prevent urine being reused on land for food production (van Velzen et al., 2013).

One of the current developments taking place in the Netherlands is separate urine collection from portable urinals at events (Wouter de Buck, personal communication, October 18, 2013; Edgar Zonneveldt[87], personal communication, January 21, 2014). This has already been applied at several large-scale events such as Pinkpop, but also with smaller events in cities (Martin Wilschut, personal communication, October 25, 2013; March 13, 2014). Some examples are Tilburg, where separate

[86] Parenco has some doubts concerning pathogens in the sludge from the communal WW that might contaminate its production process: At present, Parenco recycles the water that comes from dewatering its sludge back into the production process. When combining the sludge digestion and dewatering stages with the communal WW from the WWTP, some remaining pathogens might be transferred to the production process. Another obstacle might be the nature of both parties. With the water board being a public institution and Parenco being a private company, might result in difficulties for collaboration (Rinus van der Molen, personal communication, March 13, 2014).
[87] Sustainability expert at the municipality of Amsterdam, the Netherlands.

collection took place during its annual carnival (see Figure 6-14) (Jan-Evert van Veldhoven[88], personal communication, November 1, 2013), or the city of Nijmegen, during its annual 'Levenslied' festivity (Martin Wilschut, personal communication, March 13, 2014). The cities of Leiden and Den Bosch also separately collect urine from portable urinals. What makes these last two cases especially interesting is the permanent investment into a urine storage tank, to be able to separately collect urine throughout the year. The use of a tank also allows for an economic feasibility of collecting urine – especially for smaller municipalities that might have smaller events and less urine produced for immediate transportation towards treatment[89]. Once the tank is full, in the afore-mentioned cases GMB BioEnergie is contacted for collection and treatment of the urine in its SaNiPhos installation. SaNiPhos is specifically designed for struvite production from urine, with a capacity of 5.000 m^3 of urine/y (GMB BioEnergie, 2010)[90]. GMB BioEnergie is currently the only (Dutch) company that provides the option for processing urine into struvite (Martin Wilschut, personal communication, March 13, 2014)[91].

The value of collecting urine at events is not only contributing to nutrient recovery, but also for bringing awareness to the public of these issues and the efforts of the water boards and municipalities to contribute to resource recovery from WW (Jan-Evert van Veldhoven, personal communication, November 1, 2013). An example of such marketing is shown in the picture below[92].

Figure 6-16: Separate urine collection from urinals at the annual carnival, Tilburg, the Netherlands. Source: adopted from Richard Stomp, 2013.

[88] Senior wastewater engineer at water board 'De Dommel'.
[89] In general, the costs of transport are determined by volume of urine collected and distance that needs to be travelled. This makes collection and immediate transport towards treatment not feasible for small independent events (Martin Wilschut, personal communication, March 13, 2014). With the use of a tank, a municipality can first accumulate sufficient volume of urine for transportation.
[90] For more information on SaNiPhos see https://www.youtube.com/watch?v=PbNmGldYxWs&list=UUVjbXhmgXn2xfz7eVzuLp4A&index=2&feature=plcp
[91] At the end of 2013, a WWTP in Amsterdam West, also started with P recovery and recycling through struvite precipitation. This is however not based on a technology for urine only. The technology used is called 'Airprex' and it processes the anaerobically digested sludge from communal WW for the forming of struvite. More information on this can be found in the report by STOWA (2012).
[92] Here, Tilburg's identity as 'Kruikenzeikers' (peeing in a jar) was used as a marketing stunt to attract attention to the P(ee) topic. This identity is related to the time Tilburg had many textile factories where workers collected their urine in a jar for 'treating' the textiles (Jan-Evert van Veldhoven, personal communication, November 1, 2013). For more information see http://www.textielmuseum.nl/nl/tentoonstelling/de-wollendekenfabriek-1900-1940

Separate urine collection at events is also something a municipality can have influence on. For an event to take place, usually permits are required by the municipality. In these permits, the requirement for separate collection and treatment of urine could be taken up. The implementation is such requirements are currently being investigated in the city of Amsterdam (Wouter de Buck, personal communication, October 18, 2013). Another option would be separate collection of urine from buildings (schools, offices, apartments etc.). Whilst a previous study on this option, conducted for the city of Amsterdam (van Velzen et al., 2013), showed potential[93], it is not considered in this thesis. This has to do with the limitations of the municipality, which are addressed further in section 6.3.1.2.

The second option is separate collection and decentralised treatment of black water (urine and faeces). As mentioned in the previous subchapter 6.2.1.1, this is already practised in the NIOO building. Separate collection and treatment of black water could also be combined with the instalment of a kitchen grinder for disposal and transport of food waste via the sewer. The instalment of kitchen grinders is common in North America, Australia and Japan (Kalmykova et al., 2012; Kujawa-Roeleveld and Zeeman, 2006). In a pilot project in Gothenburg that implemented kitchen grinders, 80 % of food waste (in fresh weight) separation has been achieved (Kalmykova et al., 2012). Moreover, the addition of food waste from kitchen grinders allow for more biogas to be produced from anaerobic black water digestion (van Velzen et al., 2013). A prominent example of this found in the Netherlands, is the district Noorderhoek in the city of Sneek. The characteristics of this pilot project are as follows (adopted from Everard (2013)): Residential aged apartments designed for 600 residents. Vacuum toilets are installed and the black water, together with kitchen waste, is anaerobically digested (under mesophilic conditions of 35°C). Thereafter, there are steps for nitrogen removal and P recovery. The effluent is discharged to the sewer system.

Research and experience has shown that such concepts are best applied on new building sites (Everard, 2013; van Velzen et al., 2013) and also the municipality would only consider this feasible on new building sites, according to Harry Post (personal communication, March 13, 2014). Although a separate collection method (vacuum toilets) could fairly easily be installed in renovation projects, from the perspective of P recovery and recycling, this has little use if the waste stream is eventually discharged to the sewer. When applying DESAR concepts, scale is also important to consider. Harder (2012) explains this is due to the irregular nature of black water production (people are away on holiday or have a party with a lot of guests using the toilet). Efficient and well-functioning treatment system of black water needs to be able to deal with these fluctuations.

Nevertheless, separate collection and treatment of black water could contribute strongly to performance on recycling of P in Wageningen. Even without the instalment of a kitchen grinder, black water captures the entire P dietary intake. When including food waste, DESAR systems could divert almost all P related to human consumption originating from households for P recovery and recycling.

[93] If only 5 % of total urine produced by 2.2 million inhabitants would be collected, approximately 30 t P/yr could be recovered and recycled (van Velzen et al., 2013).

6.3.1.2. *Internal developments*

Depending on the feasibility of plans within the local context, the municipality is very willing to cooperate and seize opportunities for improved WW collection and treatment. With regard to the formulated options, the opportunities and constraints from perspective of the municipality are addressed below.

Separate urine collection at events

One of the reasons that separate urine collection would only be feasible at events (in the foreseeable future), has to do with the scope of influence of the municipality, maintenance and costs.

In principle, the municipality is responsible for the collection of WW (after it leaves the building) and ensuring proper transport through the sewer system (Arcadis, 2010). This means that the municipality has no direct influence on the actual collection method placed in buildings (toilet) and is dependent on citizens to take action and responsibility. Furthermore, the municipality of Wageningen is, what is often referred to as, a 'regie gemeente'. This means that the municipality outsources whatever possible to private parties. Real estate developing within its administrative borders is not exercised by the municipality, and therefore it has little grip on the connection and construction of sewage pipes. In addition, separate pipes for urine are not possible to sufficiently maintain by the municipality, due to its smaller diameter (Harry Post, personal communication, October 30, 2013). This maintenance is required to prevent any clogging issues due to precipitation of urine components (struvite formation, tricalciumphosphate) (Steltenpool, 2010). Finally, the diversion to separate tanks and the required transport would be a costly undertaking - especially when there is an infrastructural system present that functions and has large sunk costs (Harry Post, personal communication, March 13, 2014).

The separate collection of urine at events would be an option for Wageningen. Especially 'Liberation Day' is a big festivity in Wageningen that could provide opportunities for separate collection of urine. This is due to Wageningen's unique historical position. The capitulation of the Germans was signed here - ending WWII in the Netherlands. People from all over the country (and potentially abroad) come to Wageningen to celebrate this event. Annually, this attracts around 120.000 visitors to the city (Gemeente Wageningen, 2013e).

It is however stressed by Harry Post (personal communication, October 30, 2013), that there are relatively few events in Wageningen and that investment into the additional transport and a urine storage tank is not considered feasible. On a more regional scale however, this is an interesting possibility. The 'Platform Water Vallei en Eem' (PWVE), which is a cooperation between the water board and the municipalities, would be an ideal initiator in this. Especially, since the municipality has little time, space and money left to explore and develop such innovative concepts, next to its required operational work on the sewer system (Harry Post, personal communication, March 13, 2014). Moreover, the coordination and responsibility of separate urine collection at the event itself has proved challenging[94], and sanitation companies that provide the toilets and urinals also need to

[94] For the realisation of P recovery into a final product (such as struvite), there are three cost factors involved, namely: (i) coordination and organisation of local collection, (ii) transport and (iii) treatment (Martin Wilschut, personal communication, March 13, 2014). The first has proven the most difficult: Separate collection requires two different trucks

involved (Martin Wilschut, personal communication, March 13, 2014). The joint efforts of municipalities and the water board in PWVE, could better bear the organisation of such an undertaking (Harry Post, personal communication, March 13, 2014).

Separate black water collection and kitchen grinder

Although the municipality aims to install vacuum toilets for its newly renovated city hall (see 6.1.1.), the implementation of a DESAR system in the near future - with separate collection and treatment of black water through vacuum toilets (potentially combined with a kitchen grinder) - appeared to be impossible in Wageningen. This again has a lot to do with costs, lack of influence, responsibility for maintenance, but also health risks.

An important aspect is costs. Overall, implementing DESAR is not cheap and requires a lot of change to the current system, maintenance, a complicated piping system and careful instructions (van Velzen et al., 2013)[95]. In addition, there are large sunk costs of the current sewer system that has sufficient capacity and works well. This means that areas where infrastructure is present and buildings are being renovated, it is very unlikely that the municipality will take a leap and invest in new separate infrastructure (Harry Post, personal communication, March 13, 2014). From a cost-perspective, opportunities for DESAR concepts are thus limited to new construction sites – especially if the construction site is relatively difficult (due to distance) to connect to the current system (Harry Post, personal communication, March 13, 2014). Despite an expected growth of Wageningen (5.9 % between 2012-2020 (Rijksinstituut voor Volksgezondheid en Milieu, 2014), there is little to no new construction planned on land *owned by the municipality* according to Harry Post (ibid.). There are opportunities on land owned by the WUR: for instance a Campus Plaza is going to be built due to the growing number of students. For the Campus Plaza, it is decided by the WUR that no decentralised sanitation concepts are introduced and there will be a regular sewer connection (Gemeente Wageningen, 2013f)[96]. As already addressed above, the municipality has little control over the collection method, the connection and construction to the sewer system at new building sites. Especially construction that takes place on private terrain, such as land owned by the WUR (see Appendix VI: Land owned by the WUR in and around Wageningen, the Netherlands).

Despite these limitations, it is possible for a municipality to encourage the use of DESAR, by registering in the ordinance for connection to the sewer system at a new construction site, that black and grey water should be separated. Also a demand could be made for a smaller diameter of sewage pipes, that makes discharge on the regular sewer system difficult (Berg et al., 2013). However, the first measure could lead to separate grey water collection only and having the remaining black water (holding most P) still discharged to the regular sewer system. The second

(one for portable urinals and one for regular toilets), which is higher in costs and more challenging to organise. In general, the costs of transport are determined by volume of urine collected and distance that needs to be travelled. This makes collection and immediate transport towards treatment not feasible for small independent events (Martin Wilschut, personal communication, March 13, 2014). This is another reason for a municipality that has smaller events to invest in a separate urine storage tank to first accumulate sufficient volume of urine for transportation.

[95] The total investments of DESAR concepts, of which kitchen grinders appear to be a very high cost factor, does not seem to weigh up to the benefits (amount of biogas produced) (van Velzen et al., 2013).

[96] Although the WUR has expertise, knowledge and opportunity on its own terrain to explore and implement decentralised sanitation concepts, this decision has to do with the identity of the WUR. It has decided it wants to be a frontrunner, but no innovator. An innovator invests in pilot projects and the WUR only wants to invest in proven concepts to avoid any risks (Kimo van Dijk, personal communication, March 16, 2014).

measure could prevent such black water discharge, but Harry Post (personal communication, March 17, 2014) explains that this is not easily put into practice. If demands are made by the municipality for smaller discharge sewage pipes (for example diameter of 125 mm), then it would still be possible to discharge on the sewer system, whilst maintenance (similar to urine pipes discussed before) would become almost impossible. The municipality also does not believe such forceful measures would be the way to ensure new sanitation systems. The municipality would rather actively cooperate with real estate contractors that have purposefully made the decision for different sanitation systems (ibid.).

Furthermore, if separate collection of WW streams were to be implemented, the required piping system presents a challenge in being able to do so. Harry Post (personal communication, October 30, 2013) explains that the current infrastructure consists of so many different pipes and colours, that a wrong connection is easily made by a real estate developer (van Uffelen, 2003). After all, the primary goal of sanitation ought to be health and safety according to Martin Wilschut (personal communication, March 13, 2014).

These challenges basically exclude the option for separate collection and treatment of black water for the time being. This leaves only separate urine collection from events as a potential strategy to explore, as this is considered feasible on a regional scale. Below, the infrastructure is presented and the estimated impact of this measure on the P recycling is calculated for Wageningen only.

6.3.2. Wastewater: alternative strategy

6.3.2.1. Description of infrastructure

What makes events ideal is that the separate collection infrastructure is already present in the form of portable urinals at events. In addition to portable urinals that are only used by men, also so-called 'dixis' (regular toilets for urine and faeces) are present. The choice for separate urine collection, thus results in the need for two trucks that collect and transport the excreta to avoid mixing pure urine with combined excreta and toilet paper.

The separately collected urine is destined for processing at GMB BioEnergie in the SaNiPhos installation. As explained earlier, transport costs are an important part in making separate urine collection economically viable. With Wageningen having mostly small events, it would not be feasible to immediately collect and transport towards GMB BioEnergie. Therefore, a urine storage tank needs to be present in or close to Wageningen. After this has reached full capacity, GMB BioEnergie can come and collect the urine (this is also practised in Den Bosch according to Martin Wilschut, ibid.).

6.3.2.2. Performance on P recycling

On an annual basis, 28 events in Wageningen take place (Stichting ondernemensfonds Wageningen and Gemeente Wageningen, 2014). The most important event is Liberation Day. Apart from this event, it became clear, that not many events make use of portable urinals. Eventually, only 3 events[97] were identified that make use of portable urinals: Liberation Day, Wageningen Woetstok

[97] Only events were contacted that require the use of portable urinals (taking place outside, minimum of 500 visitors, duration longer than 2 hours, because otherwise expected that portable urinals are not required). Of 28 events, eventually 10 were contacted, of which 8 responded and an additional 2 (apart from Liberation Day) made use of portable urinals.

and AID (student introduction festival). The number of visitors are 120,000, 2,000 and 2,500 respectively (Gemeente Wageningen, 2013e; Casper Bijl[98], personal communication, March 18, 2014, Twan Cortenraede[99], March 18, 2014, Sandra Tiebosch[100], personal communication, April 8, 2014). Although the first two events are only one day, the AID lasts for five days and thus the amount of P/d from this event was multiplied by five (AID, 2014).

The total amount of P from the collected urine was cross-calculated: one calculation was made using information on the amount of P in fresh urine (g P/m^3) multiplied by amount of urine expected to be excreted at events[101] (Karak and Bhattacharyya, 2011; Maurer et al., 2006). The other calculation was based on average male (between 14-69[102]) dietary P intake, of which 67 % is found in urine (Karak and Bhattacharyya, 2011). The total amount of urine that can be collected on an annual basis is slightly more than 50 m^3. The cross-calculations resulted in the estimation that only between 0.03-0.07 t P could be annually diverted from Wageningen. From this amount of P, 90 % is recovered and recycled in the form of struvite in the SaNiPhos installation at GMB BioEnergie[103]. The residual liquid from the process is discharged on water bodies via a WWTP (GMB BioEnergie, 2014). The impact of the strategy is almost none, when viewed within the whole of P input (51.2 t P/yr). In the SFA below (Figure 6-16), the strategy and its impact is also visually illustrated and circled red (<F62>).

[98] Employee at café Loburg in Wageningen that hosts Wageningen Woetstok

[99] Secretary of the AID (introduction for new students), Wageningen.

[100] Policy employee at the department of Economic Affairs of the municipality of Wageningen.

[101] It is assumed half of daily urine is excreted at event. Only men can use portable urinals. On average, an individual produces 1-1.5 L of urine (Karak and Bhattacharyya, 2011). Assumed urine is 1.5 L/d - since men are expected to drink a lot at events.

[102] The average dietary P intake of males between 14-69 was calculated, because it was assumed young children and fairly old people won't use portable urinal

[103] To give an indication of the amount of struvite produced from this urine: one m3 of urine is said to produce around 2 kg struvite (Martin Wilschut, personal communication, October 25, 2013). The collection of urine at events would thus result in 100 kg of struvite.

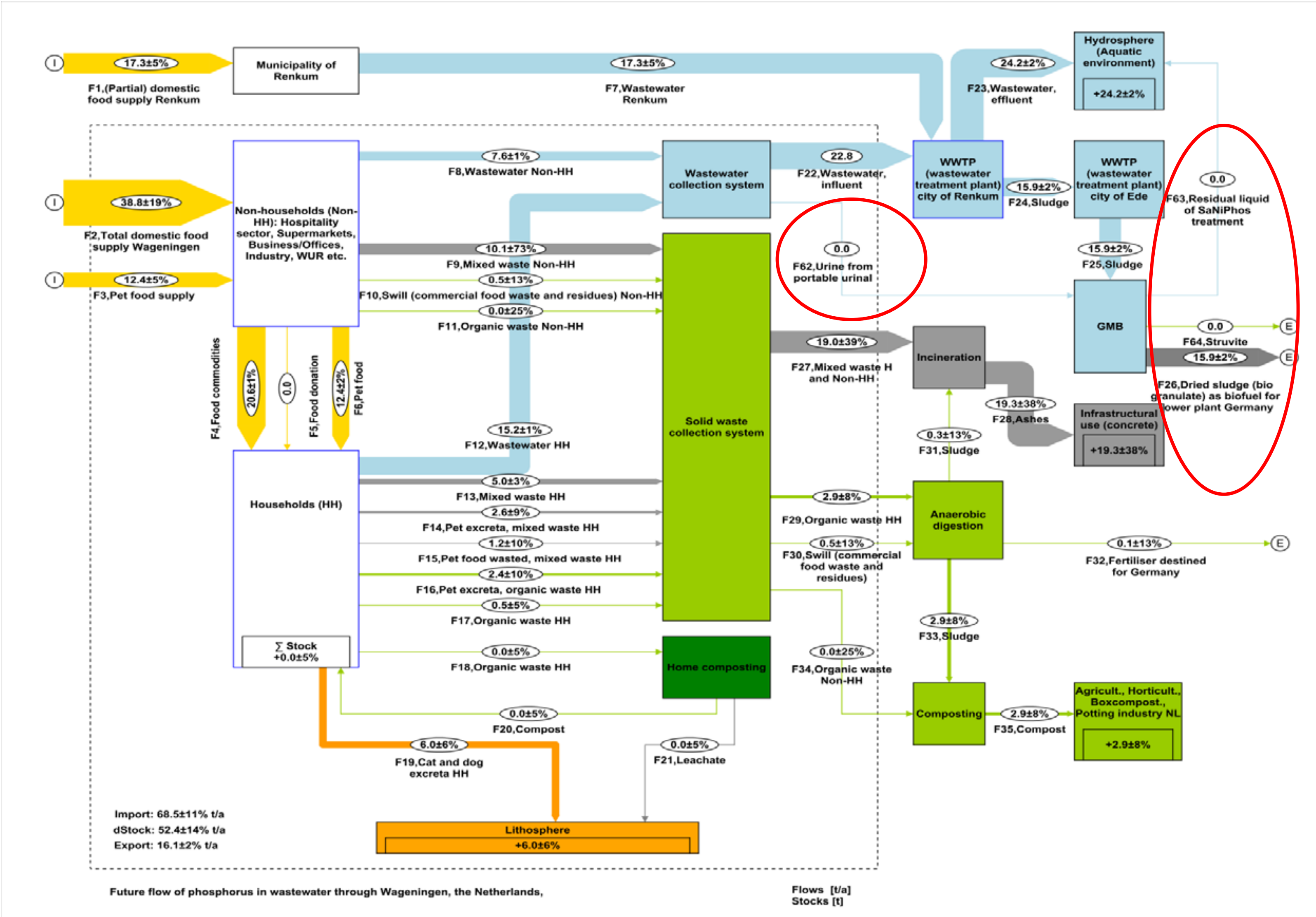


Figure 6-17: SFA of P in t/yr, Wageningen, the Netherlands, potential scenario wastewater

6.3.3. Municipal solid waste: current developments

6.3.3.1. External developments

National context

At present, there are developments that push the municipalities to increase the collection of organic waste. One important regulative driver is the proposal known as 'Van Afval Naar Grondstof' (from waste to resource) formulated by state secretary Wilma Mansveld of the Dutch Ministry of Infrastructure and Environment. This proposal is driven by the notion of a 'circular economy', in which waste is seen as a source of value for future products and the importance of maintaining natural resources for future generations is stressed. Thereby taking a radically different viewpoint than the current linear 'take-make-dispose' model (Ellen MacArthur Foundation, 2013; Mansveld, 2014). The proposal states the ambition to halve the amount of MSW that is currently being incinerated and landfilled within the upcoming ten years. It also states that the targeted separation rate for all household MSW to be achieved is 60-65 % in 2015 and 75 % by 2020. In 2010, the percentage of organic waste separated at source in Wageningen was only 51 % (Gemeente Wageningen, 2012a). Of total mixed waste collected in 2011 (178 kg/c) approximately 36 % was found to be organic waste (a little over 64 kg/c). Keeping in mind that the Dutch study by Van Westerhoven and Steenhuisen (2010) on the destination of household food waste, reported 78 % of total food waste (representing 50.4 of total 64.6 kg/c) ends up in the mixed waste, there is room for much improvement (Gemeente Wageningen, 2012a).

Furthermore, the value of organic waste (and in particular food waste) is another important driver. At present, organic waste is used for the production of compost and/or biogas, with the latter serving as an alternative to fossil fuels. Although compost is priced fairly low (production of compost provides no profit at the moment for waste processors) compost is a valued product on the domestic market as a soil conditioner[104] (Wim de Jong, personal communication, November 8, 2013, Nortcliff and Amlinger, 2001; Weinfurtner, 2001). Several grades of compost already exist to ensure it is a marketable product that can be sold. The higher the quality, the better priced (examples of high-quality compost are potting soil and 'boxcompost' for livestock[105]) (Wim de Jong, personal communication, November 8, 2013; Vereniging Afvalbedrijven, 2013a). In addition to these relatively low-grade applications, it is found that organic waste can be used for creation of high-value products. Some examples of this are: bio-plastics, extracting protein for larvae production suited as animal feed, pharmaceuticals, chemicals etc. (SRE Milieudienst, 2013; Steinbusch, 2010; van Velzen et al., 2013; Vereniging Afvalbedrijven, 2013; Gijs Langeveld[106], personal communication, March 19, 2014)[107]. Achieving a higher organic waste fraction is therefore not only required from the government, but also makes an interesting business case.

[104] For more information on the beneficial workings of compost for the soil, see (Nortcliff and Amlinger, 2001; Weinfurtner, 2001a)

[105] In the case of potting soil, additional value is created as the compost replaces the ingredient peat, which is sourced from countries such as Canada for which natural habitats are often destroyed. In addition, compost can also be further treated and sold as 'box compost' which can function as an alternative to straw beds for livestock (Vereniging Afvalbedrijven, 2013a; Waninge, 2011)

[106] Organic waste expert at Vereniging Afvalbedrijven (VA), which is a business association of waste processing companies.

[107] Illustrative to these recent developments on creating value out of organic waste is Kirsten Steinbusch. She has conducted her PhD research (2005-2009) at the University of Wageningen, the Netherlands, on microbial processing of organic waste. During this research she was able to convert short-chain fatty acids into long chain fatty acids that can be a

Possibilities and pilot projects

At present, several municipalities throughout the Netherlands are experimenting with various options to improve the amount of organic waste separated at source. Highlights of these case-studies and positive experiences are summarized in a booklet by Vereniging Afvalbedrijven (VA) (2013a), which is a business association of waste processing companies in the Netherlands. Eventually 16 measures to improve organic waste collection are presented on which potential strategies can be based. However, not all options are considered relevant for the case of Wageningen. This is partly because some of the options concern mostly garden waste or focus on educational instead of infrastructural aspects, which is outside the scope of this thesis. The remaining interesting options to be considered are (ibid.)(Vereniging Afvalbedrijven, 2013a):

1) *District focused*: often neighbourhoods are distinct from one another in terms of building type, population, and population density. Being sensitive to this differences allows to develop the best waste management strategy for each particular area
2) *Reverse collection schemes:* this entails high service on collection of resources and low service on mixed waste, where valuable resources such as organic waste are collected at curb, whilst mixed waste needs to be brought to a container.
3) *Increase in collection frequency (overall and/or in summer)*: through natural decomposition, kitchen waste (in summer) can more quickly give a stench – especially when it stays in the container for a long time. To overcome this nuisance, kitchen waste is often disposed of at mixed waste. Higher collection frequency of organic waste can avoid this to a certain extent.
4) *Differentiated tariff system (diftar) with zero charge on organic waste*: a tariff system that charges high costs for mixed waste and zero for organic can give a monetary incentive for citizens to increase separation rates,

The SRE Milieudienst (2013), a partnership of 21 municipalities in the South of the Netherlands, provides some answers into what could be a best practice. It has researched pilot projects (national and international) with regard to waste collection systems and compared the results. It has found that the highest increase in organic waste fraction is achieved, if diftar is introduced that charges the amount of mixed waste produced, but collects the organic waste stream for free. Important to note is that this is most successful if mixed waste is disposed in bags, whilst a container is provided for organic waste (more space). The highest scoring municipalities were more rural than urban. These findings are supported by Gijs Langeveld, organic waste expert at VA (personal communication, March 19, 2014). He explained that especially for low-rise buildings (which are often the predominant building type in rural municipalities) the best practice for collecting a high organic waste fraction is a combination of diftar and collection of organic waste once a week. If a reverse collection system is also added, then achieved organic waste fractions are highest. Municipalities that have applied this, have seen an increase of organic waste collection ranging from 19-120 percent of the amount collected in comparison with before (Vereniging Afvalbedrijven, 2013a).

Gijs Langeveld (personal communication, March 19, 2013) purposefully makes a distinct difference between low-rise and high-rise buildings. To him it is no surprise that it is the more rural cities that

basis to produce all sorts of valuable products from organic waste – ranging from biofuels to pharmaceuticals. For more information see (in Dutch): http://www.kncv.nl/nieuws/verenigingsnieuws/hoogewerff-stimuleringsprijs-2014-toegekend-aan.148519.lynkx score the highest in organic waste collection, because the majority of buildings is low-rise with a garden (rural municipalities produce overall more organic waste per household) and space for an organic waste container (ease of separation at source). The real challenge has proven to be the high-rise buildings that have less space and ease in separating at source. Adding to the complexity of this issue is the difference among various high-rise buildings that does not allow a one size fits all. Not only the building space and presence of outdoor possibilities to store organic waste bins (balconies) are determining factors in how much waste is separated at source, but also the type of residents living there and their attitudes towards waste handling (students, elderly people, rich, poor etc.). Moreover, the organic waste stream is also often polluted with non-organic waste, which results in organic waste streams being rejected at the waste processor and being sent to incineration after all (ibid.). This challenge led to many municipalities to stop collecting organic waste at high-rise buildings. Also in Wageningen not all high-rise buildings[108] currently have an organic waste collection container (Gemeente Wageningen, 2012a).

Gijs Langeveld (personal communication, March 19, 2014) explains that he has been assigned to currently research best practices and pilots specifically targeting waste collection systems in high-rise buildings. Therefore, no robust strategy can be formulated yet and the possibilities are most likely always dependent on the local circumstances. Options mentioned by Gijs Langeveld (ibid.) are for example: the use of passes for shared collection containers to minimise pollution with other waste. This combined with a small bin in every household and biodegradable bags for disposal of organic waste, provides a low threshold for separation at source (as it prevents unwanted odours in the household). Also diftar seems to work fairly well of which the city of Västerås, Sweden, is a good example. Here, households (including high-rise) are obliged to sign a contract with the municipality regarding their waste streams. Citizens could choose between home-composting organic waste and container for mixed waste, container for organic waste and mixed waste and only a container for mixed waste. The latter was by far the most expensive option for the citizens (almost double the amount), thereby stimulating citizens to separate their organic waste (Avfall Sverige, 2009; Guziana et al., 2011).

6.3.3.2. Internal developments

In Wageningen itself, also trials on new MSW collection schemes are being tested in the district 'Noordwest' and 'Wageningen Hoog/De Eng'. These experiments only started in 2013 (Gemeente Wageningen, 2012a), and were therefore not reflected in the 'current situation' of the SFA with the base year of 2012. These trials are thus taken up in the formulation of potential strategies, since the municipality has already invested in these waste collection schemes. In its waste management strategy, priority is given to plastic, but also organic waste. Especially since it contributes to environmental policies such as reduction of CO_2 emissions[109], it represents the highest fraction (in weight) of mixed waste and the cost of processing mixed waste is much higher than organic waste (ibid.). The target is an increase of 10 % in organic waste separated at source (ibid.)[110].

[108] The number of high-rise buildings with or without an organic waste container was not specified (Gemeente Wageningen, 2012a).
[109] Use of biomass for production of biogas (Gemeente Wageningen, 2012a).
[110] No exact time-span to achieve this for the whole of Wageningen is given. It is stated that the calculations are based on assumptions for now. First, the municipality wants to await the outcome of the one-year pilot testing and see how well the chosen measures work (Gemeente Wageningen, 2012a).

In each district a slightly different MSW collection scheme is applied to evaluate which measures give optimal results. Even more importantly, the municipality aims for a district approach, which means the municipality already intends to realise option 1. The desire for such a district approach was expressed by inhabitants and made sense as these neighbourhoods also have different characteristics (in space for containers, density of buildings and building type) (Gemeente Wageningen, 2013g, 2012a; Rike van de Wiel[111], personal communication, March 13, 2014)

In the district Noordwest, that has high-rise and low-rise buildings, a reverse collection scheme is implemented (second option), where mixed waste containers are placed at a distance of maximum 250 m (Gemeente Wageningen, 2013h). At present, all high-rise buildings in Wageningen have a mixed waste container inside the building or in close vicinity (Gemeente Wageningen, 2012a). During the trial, the mixed waste containers for high-rise have been relocated in the area, to also accommodate for residents in low-rise buildings in ensuring a maximum distance of 250 m. The new mixed waste containers can only be opened with passes, so only residents can make use of the containers. To avoid people having to carry heavy bags with mixed waste, the municipality also encourages residents to buy environmentally friendly kitty litter according to Rike van de Wiel, policy advisor environment and sustainability at the municipality of Wageningen (personal communication, March 13, 2014) [112]. For residents in low-rise buildings, the organic waste can be disposed of in mini containers and is collected every two weeks at the curb (Gemeente Wageningen, 2013i). Generally, residents in high-rise buildings in Wageningen have the opportunity to separate organic waste in a small waste bin (10 L) and dispose of the waste in an organic waste container close to the building (Rike van de Wiel, personal communication, March 13, 2014). However, not at all high-rise buildings in Wageningen such a collection container for organic waste are placed. Therefore, it cannot be said for certain that at present the residents of Noordwest in high-rise buildings all have the opportunity to separate organic waste. In its waste management strategy, Wageningen formulates the aim of pilot testing a pass system for access to organic waste containers to avoid pollution of the waste stream. Wageningen also aims to research further possibilities in high-rise buildings to increase the organic waste stream (Gemeente Wageningen, 2012a). At present, talks and consultation has started with residents associations among other (Rike van de Wiel, personal communication, March 13, 2014).

For the district Wageningen Hoog/De Eng, which is a district that is not densely populated and has more space per household (Gemeente Wageningen, 2013j), mixed waste is also discouraged. Mixed waste containers are provided and collected at the curb, but only once a month. The organic waste on the other hand, is collected every two weeks. This frequency is however the same throughout Wageningen. With this ‘conventional’ collection frequency, option 3 is currently not being implemented at the moment.

Important to notice is that Wageningen has also not introduced diftar (the fourth option). This decision is in contrast with the experiences of seemingly similar small and rural municipalities that have implemented diftar successfully (Vereniging Afvalbedrijven, 2013a). Rike van de Wiel (personal communication, March 21, 2014) explains that this has several reasons. First, it is debatable whether

[111] Policy advisor environment and sustainability at the municipality of Wageningen
[112] Kitty litter can be fairly heavy and such straining efforts can be avoided if people buy environmentally friendly kitty litter that can be disposed of in the organic waste stream (Gemeente Wageningen, 2013m).

it is worthwhile, since research also showed negative effects of diftar[113]. Furthermore, the municipality of Wageningen has specifically chosen a differentiated district approach – that does not seem to match the option of diftar. When choosing diftar, it needs to be implemented in the entire municipality (ibid.). In addition, Wageningen has a fair number of high-rise buildings, approximately 60 % of households is low-rise and 40 % high-rise (Rike van de Wiel, personal communication, March 13, 2014). This large number of high-rise buildings in Wageningen is seen as a downside for the introduction of diftar, as it would mean a necessary pass system for various waste containers (for administration and calculation of costs to household). As explained in Chapter 5, Wageningen hosts many students. Most of which live in high-rise buildings that are expected to move a lot, this would result in a complex administrative system (Rike van de Wiel, personal communication, March 21, 2014). Allers and Hoeben (2009), from the Dutch research institute COELO, also stressed that municipalities have to invest fairly heavily to implement diftar and the expected complexity might not make such a costly administrative system feasible for Wageningen. Therefore, other collection schemes as an alternative to diftar are first being researched (ibid.). Depending on future outcomes in general and outcomes of the pilots conducted with diftar in the neighbouring town of Veenendaal there might be a change of attitude towards introduction of diftar (ibid.).

Finally, in the waste management strategy of Wageningen home-composting is not stimulated (Gemeente Wageningen, 2012a). It is not considered a full alternative for organic waste, because not all organic waste produced in a household can be composted, which means there is still a need for collection of remaining organic waste. Furthermore, it is questioned if it can sufficiently compete with engineered composting processes in quality and final destination (ibid.).

6.3.4. Strategy infrastructure

It becomes clear that only the first 2 options (district focused and reverse collection) are currently explored by the municipality. Whilst an increase in collection frequency might still be possible, diftar does not sufficiently match with the strategy formulated by the municipality. The limits and future plans of the municipality are leading in the formulation of strategies to ensure its (short-term) feasibility. Combining the current MSW management strategy of the municipality with some of the known measures that could complement current trials result in the following strategy:

6.3.4.1. Description of infrastructure

Low-rise buildings

1) More frequent collection (once a week)
2) Reverse collection scheme with pass for mixed waste container OR Less collection in low densely populated areas
3) Home-composting is stopped

Discouraging mixed waste is maintained and depending on the density of the area, reverse collection or less frequent collection is applied (see Figure 6-17). An alteration to the current pilots taking place is the increase in collection frequency of organic waste from mini containers. Especially since this

[113] Research institute COELO mentions that housing expenses in municipalities with diftar have proven to be distinctively higher and the estimated effect of diftar are less than expected (Allers and Hoeben, 2009).

was found to be part of the best practice (see pilot projects and possibilities). Furthermore, the case of the municipality Horst aan de Maas (Vereniging Afvalbedrijven, 2013a) that applied an increase in collection frequency gained much success. Home-composting is stopped due to lack of its insignificant P flow and the intention of the municipality to stop any further stimulation of home-composting[114].

Figure 6-18: Reverse collection system. Source: adopted from Gemeente Wageningen, 2013k.

High-rise buildings

1) Small bins, biodegradable bags, shared collection container for organic waste, with pass
2) Reverse collection (mixed waste container is not in building)

The small bins of 10 L that are currently available to (most) residents in high-rise buildings in Wageningen are kept. Several reasons that argue against the introduction of larger city bins which are used in Utrecht are given by Gijs Langeveld (personal communication, March 19, 2014): First, city bins are from an occupational health and safety viewpoint not responsible for the workers collecting the waste, as they are simply considered too heavy once filled up with organic waste. Furthermore, the increase in size would also allow for organic waste to remain too long in the city bin. Here, the natural formation of volatile organic compounds (VOCs) containing sulphur due to microbial processes causing malodours and potentially have a health impact such as airway irritation (for more information, see Mayrhofer et al., 2006; Statheropoulos et al., 2005; Wilkins, 1997; Wu et al., 2010). Finally, it can also be questioned whether there is always sufficient space for larger bins in the

[114] Home-composting also results in local accumulation of P of which it is not always certain whether it finds its way back to agriculture (Wim de Jong, personal communication, November 8, 2013).

residents' homes. To ensure a low threshold in separating organic waste at source, the use of hygienic biodegradable bags is proposed, combined with an organic waste collection container that is easily accessible for residents. To accommodate easy access, organic waste containers would replace the mixed waste containers, which are at present found within buildings or in very close vicinity (Gemeente Wageningen, 2012a). The ease of disposing of organic waste is thus contrasted with the disposal of mixed waste. In addition, a pass for the organic waste container might aid in avoiding unwanted (non-organic) waste. This could in turn stimulate better organic waste separation at source, since a fouled organic waste container proved to be a source of nuisance to residents and affected the willingness to separate (Rike van de Wiel, personal communication, March 13, 2013)[115].

Due to the decision against diftar (for now) by the municipality of Wageningen, this proposed waste collection system is based on a pilot project that was introduced in the neighbourhood of Lunetten in the city of Utrecht, the Netherlands[116]. Since the pilot in Utrecht has already been evaluated and the average results (after one year) are known, this allows for estimating the effect in Wageningen of such a MSW management strategy on the collection of organic (food) waste and the associated P. It can be noticed that the proposed strategy is not bold, but only a slight alteration to current trials taking place in Noordwest and Wageningen Hoog/De Eng. This is for the following reasons: (i) it enhances the feasibility of implementation; (ii) it adheres to the limitations and opportunities within the local context. The local context is important to consider, because the case of diftar - that is successfully applied in (what could be categorised as) similar municipalities - was not found very suited for Wageningen, which clearly shows that simply copy-pasting is not sufficient. Finally, (iii) there is a lack of knowledge in the solid waste community of the preferred and proven strategy to enhance the separation rate of organic waste, with a specific emphasis on high-rise (see 'Possibilities and pilot projects').

6.3.4.2. Performance on P reuse

With the proposed strategy being based on the pilot in Lunetten, the outcomes of this pilot are thus used to make an estimation what the effect might be for Wageningen. Here, no distinction is made between effects on low-rise and high-rise buildings, since this information was not sufficiently available and reliable[117]. Seeing that Lunetten is a mix of high-rise and low-rise buildings, this afore-mentioned increase is assumed to be an average that could be applied to Wageningen. An important additional factor in the calculation of the effect of this strategy on the reuse of P is pet excreta. It is expected that the reverse collection scheme gives inhabitants the incentive to dispose of the pet excreta in the organic waste container. Officially, cat and dog excreta would be excluded due to hygienic reasons. However, cat excreta are allowed in the organic waste container with environmentally friendly kitty litter (Milieu Centraal, 2014). Rike van de Wiel (personal communication, March 13, 2014) mentioned that buying environmentally friendly kitty litter is also encouraged by the municipality: Kitty litter can be fairly heavy and a reverse collection scheme

[115] Experience from inhabitants of Lunetten also agree that a pass system works really well (Gemeente Utrecht, 2013a)

[116] In the pilot of Lunetten, which has a combination of high-rise and low-rise buildings, reverse collection is also applied with the use of a pass for mixed waste containers and a maximum distance of 125 m (similar to Noordwest pilot). For low-rise buildings, mini-containers for organic waste are provided and are collected once a week. High-rise buildings have a city bin (30 litres) that can be placed at the curb and is collected once a week (Gemeente Utrecht, 2013b).

[117] The municipality of Utrecht does provide information from a sorting analysis conducted at high-rise and low-rise buildings. This is however only a snapshot and merely states the amount of organic waste (in kg) present in mixed waste (Teuns, 2013). Not the actual increase in the organic waste stream.

requires citizens to bring their mixed waste to a container. Such straining efforts can be avoided if people buy environmentally friendly kitty litter.

From the calculations the following effects of the MSW management strategy were found with regard to P reuse: In the case of Lunetten, there was an increase of 3 kg organic waste/c/yr separately collected, which is a 108 % increase from the current situation[118]. The achievement of 3 kg/c is relatively low when considering 50.4 kg/c of *food waste* and 64 kg/c of *organic waste* is still found in the mixed waste stream (see 'External developments'). In addition, the set target by the municipality of 10 % increase in collection of organic waste would also not be reached. Yet, what does this ratio mean for the amount of P diverted to the organic waste stream? Due to a lack of more specific data, this percentage (converted to the ratio 1.08) was one on one applied to the P found in the organic waste flow[119]. When applying this ratio to the amount of P that could possibly be diverted in Wageningen, it only results in an increase of 0.04 t P/yr. In contrast, the expected effect of this strategy on P related to pet consumption is much higher. When assuming (as explained above) that all excreta from small pets and some of the excreta from cats is diverted to the organic waste stream due to a reverse collection system, this could result in a total of 0.82 t P/yr being reused. This confirms the importance of considering P in pet food, as the impact of the MSW strategy appears to be the highest for these P flows (representing 95 % of the total additional P reuse achieved by this strategy).

When combining the diverted P flows of pet excreta and food waste, the MSW strategy has some impact, albeit very little in comparison with the total P input of Wageningen (not even 2 % of 51.2 t P/yr input is additionally reused). The impact is circled red in the SFA below (Figure 6-18). In comparison with the overview of the current situation, no clear difference can be noticed.

[118] In an earlier newsletter (Gemeente Utrecht, 2013), the municipality mentions a rise of 37 to 42 kg/c/yr of organic waste. However, the source stating 3 kg/c/yr is from February of 2014 (de Rijk, 2014) and is thus considered more reliable and accurate.
[119] No information was known on the exact composition of the additionally collected organic waste (is this mostly kitchen or garden waste?) to assess the amount of being diverted more accurately (de Rijk, 2014).

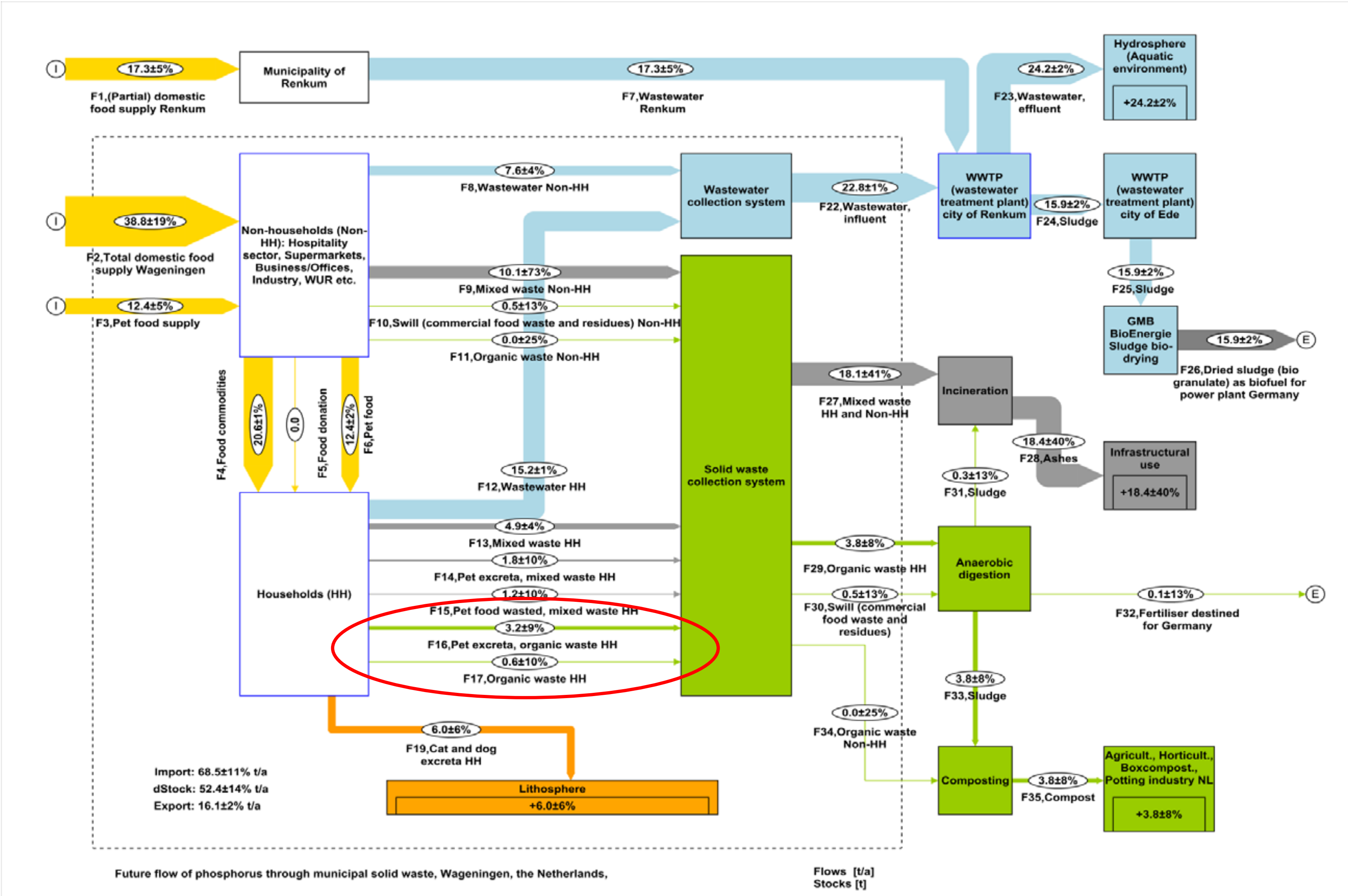


Figure 6-19: SFA of P in t/yr, Wageningen, the Netherlands, potential scenario municipal solid waste

6.4. Conclusion

This chapter showed that the waste management system, which strongly determines the flow of P, can be divided into WW and MSW. Of the total P input into Wageningen, pet food appeared to be a relatively large flow – accounting for approximately 24 %. Not all P input could be accounted for in the calculation of P output. This residual flow (<F41>) is relatively large: 15 % of the total P input. The P output via the waste management system was found to be nearly equally distributed over WW and MSW. There is no P recycling taking place, since all P in WW is lost. Here, it is the specific local context of the WWTP that provides no incentive for P recovery and recycling. Some of the food related P flows from Wageningen are reused via MSW in the form of compost, and in total amount to 6 % of the total P input. Most of this P reuse was related to pets. From a municipal perspective, alternative strategies on the level of WW management were limited and only separate urine collection from events was considered a potential option. Here the regional scale proved to be of importance, as a larger scale is expected to make this strategy more feasible in terms of scale, costs, organisation and responsibility. In comparison with WW, strategies for MSW had a higher contribution to the improvement of P reuse and recycling. In the proposed (collection) strategy, a distinction was made between low and high-rise buildings, of which the latter presented the strongest challenge. The proposed reverse collection system, which is valid for both low- and high-rise is the most important, since this is expected to stimulate disposal of pet excreta in the organic waste container. Diverting this particular waste stream showed to be a key contributor in improving the amount of P reuse. When combining the efforts of both strategies, an increase of approximately 1 t P reused/recycled can be additionally realised on an annual basis (an additional 2 % of 51.2 t P/yr input). The strategies thus appear to only slightly contribute to a higher performance of P reuse and recycling in Wageningen. In Chapter 7, the most important findings, implications for the municipality and how they relate to the larger context, are more discussed in depth.

7. Discussion

7.1. Introduction

The findings of the 'baseline' and 'alternative strategies' are further explained and discussed in depth in this chapter. This is done through comparison with other, urban substance flow analysis (SFA) studies on phosphorus (P), and integrating the Social Network Analysis (SNA) findings of my thesis colleague Timo Eckhardt. Thereafter, the implications of these findings for the municipality of Wageningen are discussed and how the findings relate to the larger context. The latter consists of two parts. The first discusses the expected difference between small and larger municipalities The second part elaborates on how urban areas relate to national and global P issues. Furthermore, the methodology used in this thesis, and its limitations, are addressed. Finally, a conclusion of the main findings is presented.

7.2. Baseline

The first striking finding regarding P output is the amount of P in wastewater (WW) being nearly equal to the amount in municipal solid waste (MSW). This finding corresponds with Kalmykova et al. (2012), as their research on the city of Gothenburg, Sweden, shows that the amount of P found in MSW is equal to WW. Interesting is that Kalmykova et al. (ibid.) did not limit their study to P in food only, yet included nearly all urban P flows. Despite this difference in approach, the overall outcome on this aspect is the same. Potentially this is explained by the fact that food is found to be the most dominant P input in urban areas (see section 1.2). In the specific study by Kalmykova et al. (ibid.), the input related to food (including pet food) totalled 388 t P/yr which accounted for 78 % of total P input. Therefore, the additional flows considered in Kalmykova et al. (ibid.) might not make that much of a difference to the overall picture. Another potential explanation is that the remaining P flows also have an equal division over WW and MSW.

Despite the fact that Kalmykova et al. (ibid.) support the finding of this thesis, a cautious note is required with regard to the amount of P found in MSW. This is due to uncertainties in data[120], combined with the mass balance principle of SFA methodology - that dictates whatever enters the system, needs to leave as an output or retain as a stock (see Chapter 2). Strong data uncertainties were found in the P input (domestic P input from food supply)[121] and P output of *MSW* originating from the non-household sector (also addressed in section 6.2.2 and 7.5.2). This resulted in a residual flow (<F41>) being ascribed to MSW. However, a relatively high uncertainty in P input, means that the actual amount of the residual P flow could vary greatly. Accordingly, the finding of nearly *equal* P division over waste streams has some uncertainty that needs to be taken into account. The uncertainty in the calculation of flows is further addressed in subchapter 7.5.2.

In addition to this uncertainty, two recently published reviews of SFA studies on P have actually pointed to WW as the most prominent and important P flow on an urban scale (Chowdhury et al., 2014; Cordell et al., 2012). Chowdhury et al. (2014) observed that in three of the four city scale analyses, WW was said to account for approximately 90 % of all P outflow. It cannot be said for

[120] For a complete overview of uncertainties assigned to each P flow see Appendix III: Uncertainty of flows.

[121] The initial domestic P input from food supply is based on the Dutch domestic P supply from food. The latter is estimated at 17.5 Mkg P with a large dispersion of 3.3 Mkg (Bert Smit, personal communication, November 27, 2013, publication in preparation).

certain what the reasons are for this opposing outcome. It might be precision in available information, but could also be ascribed to a difference in defined system boundaries and the context in each study. For example, the SFA conducted by Tangsubkul et al. (2005) which is taken up in both reviews, is focused on WW management and is therefore already biased. Chowdhury et al. (2014) also showed in their review of SFA studies that the inclusion or exclusion of certain sectors result in the overall SFA having a different outcome[122]. System boundaries are one of the reasons that comparison with other similar SFA studies is challenging. Especially urban SFAs are more detailed, and accordingly, show very specific characteristics that determine key flows and the emphasis of that particular context (Cordell et al., 2012). The difficulty of comparison with other SFA studies is further addressed in subchapter 7.5.1. Furthermore, the SFA studies taken up in the reviews were prior to 2012. The study by Kalmykova et al. (2012) was only published in 2012, and thus not considered in these reviews.

Nevertheless, with many SFA studies pointing to WW as the most dominant urban flow of P, combined with the concern for eutrophication taking place in water bodies (see section 4.3.5), it is probable that much of the focus, policies and measures for urban P reuse and recycling are directed to WW. This presumption was also confirmed on a conference called “Circular Economy in Cities: Focus on Phosphorus” that took place in Berlin, on January 21, 2014 (Royal Dutch Embassy, 2014). Although this conference signals there is attention for the particular topic of urban P management, there was a clear focus on P found in WW (see also Eckhardt 2014). Phosphorus in MSW was only marginally addressed, whilst recovery of P from WW took shape in actual projects taking place. Potentially this focus is also explained by the fact that P in MSW is a much less centralized stream and therefore more challenging to manage. As explained in section 6.2.1.2, for the municipality of Wageningen alone, many different waste collectors and processors are active. Moreover, it is not a case of simply applying technology to the treatment of the waste stream. With MSW, (separated) collection is also dependent on the good will of the waste producers itself (private individuals or companies). Despite these challenges, this thesis argues that urban P management is as much about MSW (as it has proven to be a significant waste stream) as it is about WW.

What also stands out in the SFA is the relatively high fraction of P related to pet consumption. One reason for this could be that pet food - especially for cats and dogs - has a relative high content of P. For comparison: an average human male and female between 19-30 years old, have a dietary P intake of 0.63 kg P/y and 0.48 kg p/y respectively. Although cats are below this, with an average P intake of 0.29 kg P/y, it is still remarkable considering its size compared to a human. Dogs are the most striking, with their dietary P intake to be estimated at a baffling 1.45 kg P/y for an average Dutch dog. What explains this dietary P intake, is that pet food contains a lot of animal by-products originating from slaughter waste, such as intestines and bone meal (Smit et al., 2010). Approximately two-third of all slaughter waste is estimated to end up in wet feed for cats and dogs (Wageningen UR Livestock Research, 2011). In feed for dogs, approximately 25 % of dry feed and 20 % of wet feed is made up of animal by-products (ibid.). Also snacks for dogs are often bones or pig ears. These animal products contain high amounts of P (RIVM, 2011a). Therefore, it is not surprising that cats and dogs with this dietary P intake and present in fairly large numbers (approx. 2.355 cats and 4.182 dogs in Wageningen) are responsible for the largest part of the total P in the pet food flow.

[122] Most of the stock in other SFA studies was retained in landfill, whilst the SFA of Tangsubkul et al. (2005) appointed most of the P stock to agricultural soil.

Compared to other studies that considered pets in a substance flow analysis of P (Kalmykova et al., 2012; Kirsimaa and van Dijk, 2013), the amount of pet food is a relative large flow of the total P input (related to food) through Wageningen. This is exemplified in Figure 7-1 below, that shows the division of P input related to human consumption and pet consumption, of the cities of Wageningen, Rotterdam (both Netherlands), and Gothenburg (Sweden) respectively. This calculation was based on the relative amount of P (in t/yr) from pets of the total amount of P from food flows entering Rotterdam (Kirsimaa and van Dijk, 2013) and Gothenburg (Kalmykova et al., 2012).

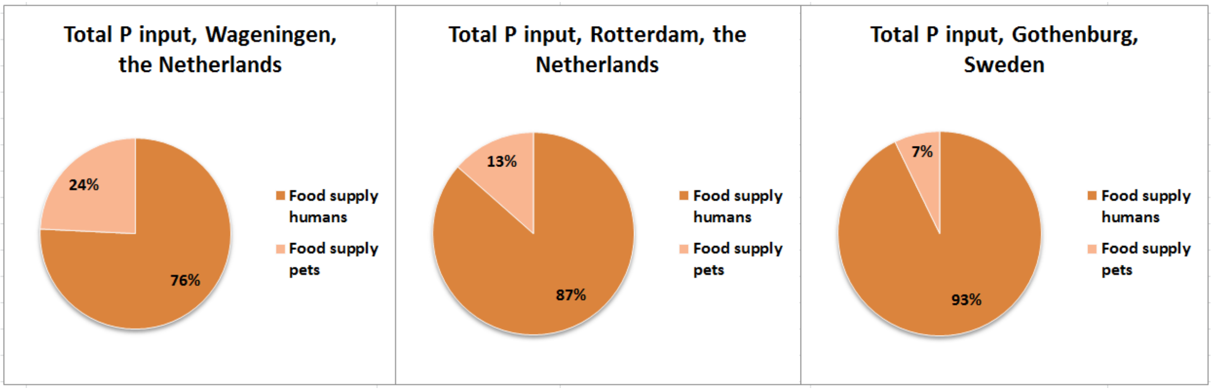


Figure 7-1: Division of total P input, from the cities of Wageningen (Netherlands), Rotterdam (Netherlands) and Gothenburg (Sweden). Calculations for Rotterdam and Gothenburg based on Kirsimaa and van Dijk, 2013 and Kalmykova et al., 2012, respectively.

This difference might be partly explained by the fact that the other studies both concerned larger cities (Rotterdam and Gothenburg) with relatively less (green) space per household for keeping pets, compared to Wageningen. For instance, calculations show that pond fish are actually responsible for a fairly large part of the total amount of P in pet food[123]. In cities like Rotterdam and Gothenburg, gardens for keeping pond fish might be scarce and they are thus not considered in the studies. In addition, some other elements are not accounted for in both afore-mentioned studies that determine the amount of P related to pet consumption: In the study of Rotterdam there was no consideration for pet food wasted, and Kalmykova et al. (2012) only included cats and dogs. In addition, the latter study also assumes a lower P intake for cats and dogs (only 0.27 and 1.2 kg P/yr respectively, instead of 0.29 and 1.45 kg P/yr in this thesis)[124]. Therefore, it can be assumed that the amount of P related to pet food in both of these studies is most likely on the low side.

The importance of considering pet food in urban P flows is thus stressed in this thesis and also supported by findings from Baker (2011). He conducted an SFA study of P of the Twin Cities Watershed (TWC), which encompasses the largest part of the metropolitan area of Minneapolis St. Paul, USA. Here, P in all products (including detergents and agricultural related activities) was considered, and it appeared pet food was the third largest P input into the area (ibid.). When limiting

[123] This is due to a combination of dietary P intake (see Annex 12, table 3 from (Kirsimaa and van Dijk, 2013) and the large number of pond fish in the Netherlands (Borst et al., 2011).
[124] The dietary P intake for cats and dogs chosen for this thesis is based on very accurate calculations made by Kimo van Dijk (Kirsimaa and van Dijk, 2013)

the study to P found in food flows only (see Figure 7-2 and the P flows related to food marked red), even 25 % of the P input can be assigned to pet food (see Figure 7-3). This case study clearly exemplifies that also in larger cities/metropolitan areas, pet food should not be underestimated and attention ought to be paid to gather sufficient data on this topic for an accurate SFA and subsequent management of urban P flows.

Table 2
Current P balance for the TCW.

Inputs	P flux (Gg yr^{-1})	% of total
Human food consumed	1.16	28.5
P-containing chemicals that enter sewage	1.37	33.7
Wasted human food	0.51	12.5
Pet food	0.55	13.5
Agricultural fertilizer	0.22	5.4
Turf fertilizer	0.12	2.9
Atmospheric deposition	0.11	2.7
Feed for farm animals	0.04	1.0
Total input	4.07	100.2

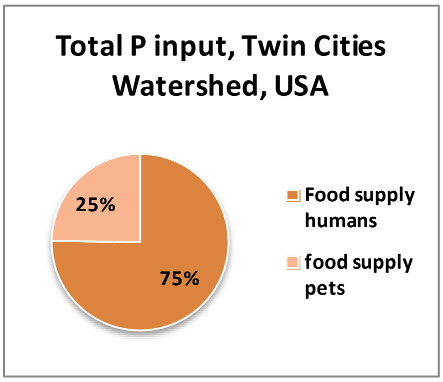


Figure 7-2: Current P Balance for the TWC. Source: adapted from Baker 2011.

Figure 7-3: Division of total P input, Twin Cities Watershed, USA.

Most of the P related to pets ends up on land and this actually accounts for a relatively large flow: approximately 12 % of total P input of 51.2 t P/yr (see section 6.2.2.4). Clearly, not all P output is (or can be) diverted to a waste management system, which might be a problem depending on the context. In the Netherlands, where soils are already saturated with P, leading to run-off and leaching into water bodies, the excreta from cats and dogs is a negative loss to the biosphere. This further stipulates the importance of accounting for P related to pets, especially in Dutch cities and countries/areas dealing with similar P issues. If P from pet excreta returning to land is negatively valued, then the same could be argued for P present in compost. However, compost is a targeted use and its load restricted by law[125], whilst pet excreta are diffuse and not controlled. Furthermore, its soil conditioning properties are very much valued on the domestic market (see section 6.3.3.1 and 7.3.1). Moreover, the water retaining properties of compost allow the soil to hold more water and as such help reduce the leaching and run-off of P into water bodies (Wim de Jong, personal communication, November 8, 2013; Alterra, 2013; Nortcliff and Amlinger, 2001; Weinfurtner, 2001).

Finally, the results show that little P from Wageningen is reused (6 %) and none is recycled. With an overall loss of 94 % of total P input, the municipality of Wageningen scores slightly better than the city of Rotterdam, where it was found approximately 99 % of P is lost[126] (Kirsimaa and van Dijk, 2013). This difference can be explained by the fact that Rotterdam does not separate its organic waste at all.

[125] In the Netherlands, areas for food production can receive a maximum of 6 t/ha/yr in compost and areas for non-food production a maximum of 3 t/ha/yr of compost

[126] Although this study also included other P flows besides food, the amount of P reuse and recycled from food waste can be considered insignificant. The report states that only 0.2 % of organic waste (accounting for 1.2 t P/yr of total 582 t P/yr) is composted and thus reused (Kirsimaa and van Dijk, 2013).

7.3. Alternative strategies

Although the emphasis of this thesis was mapping out the current situation (baseline) of Wageningen, alternative options have been touched upon that gain an understanding of the near future outlook of P management in Wageningen.

From the results it became clear that alternative strategies, within the current limitations, seem to have relatively little effect on the amount of P reused and recycled in Wageningen. In order to gain a more profound understanding of these findings and future possibilities, identified limitations and opportunities (low-hanging fruit) for implementing appropriate infrastructural measures to further P reuse and recycling, are discussed in depth. First, issues on a broader scale are exemplified that appear to either limit or support the alternative strategies for P reuse and recycling on an urban scale. Thereafter, the limitations and opportunities experienced on the local scale are addressed.

7.3.1. National context

Limitations

On a national scale there are some developments that have shown to constrain the business case of P reuse and recycling. The most important issue is the market force. This influences the demand for the end-product produced from the waste streams (in this case struvite and compost), that allow the return of P to agriculture in order to close the loop. If demand for the end-product is relatively low, this has a distinct effect on the drive for setting up waste management systems for P reuse and recycling on an urban scale. As explained in section 6.3.1.1, now and in the foreseeable future, legislative forces and especially a lack of domestic demand for struvite, make export necessary and thereby, adding to product costs. At the moment, struvite is more costly to produce than what is gained from its selling (Martin Wilschut, personal communication, October 25, 2013).

In the case of compost, there *is* a domestic demand due to its soil conditioning properties and carbon content, which is crucial in maintaining fertile soil (Vereniging Afvalbedrijven, 2013a; Zwart et al., 2013). Yet, compost officially falls under the Dutch Fertiliser Act (Visser, 2009), because the product contains P and its use should thus officially be 'restricted' in agriculture (Wim de Jong, personal communication, November 8, 2013; Visser, 2009). At the same time, a lot of compost is produced in the Netherlands (In 2012, 660 Kt compost was produced). On EU level, the Netherlands composts 28 % of its organic waste, which makes it the second-best country in composting its organic waste after Austria (Vereniging Afvalbedrijven, 2013a). The result of this 'massive' production combined with its restrictive use, is that there is no demand for all compost produced. Thereby the cost of compost becomes relatively low and thus has difficulty competing with regular fertiliser. Simultaneously, compost and organic waste in general, has versatile applications that pose opportunities to overcome this barrier, which is further discussed in 'Opportunities'.

Nevertheless, it becomes clear that P needs to become a lot more expensive to make market forces and especially farmers favour alternative sources of P such as struvite, and to certain extent compost[127], over regular mineral fertiliser such as diammonium phosphate and superphosphate (also addressed in section 4.3.6). One possibility to facilitate a stronger demand for high quality struvite and compost, is imposing restrictive regulations and standards on the permitted amount of heavy

[127] Compost is rather considered as a soil conditioner than a fertiliser and has very different characteristics than mineral fertiliser and thus complete substitute is not expected (Weinfurtner, 2001b).

metals in fertiliser on national, or even EU-level. As explained in section 4.3.3, mineral fertilisers contain a slight percentage[128] of the hazardous elements cadmium and uranium that are present in phosphate ores. This affects soils, potentially ground water and eventually food safety (Keyzer, 2010; Schröder et al., 2010). Keyzer (2010) thus argues for putting a ban on importing contaminated P. Martin Wilschut (personal communication, October 25, 2013) also explains that struvite would become a more interesting alternative to regular inorganic fertiliser if the EU restrictions on heavy metal content in fertiliser (for instance cadmium) would be expressed in kg/P, instead of kg/product[129]. Legislative measures on contaminants are becoming increasingly relevant for the EU and the Netherlands as high-grade phosphate ores are being depleted (see section 4.3.2). With the lower grade ores having higher concentrations of cadmium and uranium, it is important to ensure soil and groundwater as well as food quality and safety through such avert measures. This could either push the removal of these contaminants through further processing (increase the price of inorganic fertiliser), or the use of inorganic fertiliser would become restricted. Both outcomes could make struvite and compost attractive alternatives from an economic perspective.

Another potential inhibition is a lack of focus and/or incentive for municipalities to further P reuse and recycling. Much of the sustainability initiatives by municipalities and governmental institutions seem to focus on energy, which is mainly translated into actions to reduce CO^2 emissions. This energy focus is driven by the global concern for climate change. With EU guidelines and regulations concerning climate change prescribing its member states by 2020 to cut down 20 % on CO^2 emissions below 1990 levels (European Commission, 2014), municipalities and other public institutions such as the water boards are required to take action. In contrast to P issues, actions required on climate change have thus been institutionalised through these set guidelines. As the results of the SFA show (section 6.2.2), much of the organic waste stream from non-households, if separated, is treated as swill (commercial food waste and residues). Van Gansewinkel, a nationally operating waste collection and processing company, is known to incinerate this digestate (Maarten Duineveld, personal communication, November 22, 2013)[130]. Whilst from an energy point of view, this is very much beneficial and in general would be considered sustainable, all P is eventually lost. This example illustrate that a regulative force can drive energy goals, yet result in a more narrow understanding and implementation of sustainability, which in turn might overshadow the need for resource recovery and recycling.

Opportunities

It is in the field of MSW that market forces also present interesting opportunities. As mentioned in subchapter 6.3.3.1, there is an increased recognition of the potential and value of organic waste. In contrast to P in WW, the P reuse through separate collection of organic waste is thus value driven.

[128] (Keyzer, 2010) states that N, P and K contained in a bag of fertiliser at best covers 60% of the total composition. When calcium, oxygen, hydrogen are also considered, then 98% of the total weight is accounted for. The remaining 2 % however, according to Keyzer, are heavy metals such as cadmium and uranium.

[129] Such a measure could restrict the amount of cadmium and uranium allowed in inorganic fertilisers (see 4.3.3). If the inorganic fertilisers produced from phosphate rock do not sufficiently comply – struvite might become an interesting alternative.

[130] This might be explained by the fact that swill *can* be a very questionable waste stream of which it cannot be said for certain what is present in the waste stream. Out of precaution it might thus be necessary to incinerate the digestate if there is insufficient or trustworthy data on the content. For more information see this documentary http://www.praktijkdagbioenergie.nl/kro-documentaire-over-biogas/

This market incentive for example takes shape in the business association 'Vereniging Afvalbedrijven' (VA) of waste processors. The VA is actively engaging municipalities in exchanging best practices to enhance the collection of organic waste (Vereniging Afvalbedrijven, 2013a, 2013b). Bringing knowledge together and exchanging information poses opportunities for the municipality of Wageningen to enhance their own waste management system. An important development currently taking place is the research project of the same business association to investigate best practices for collecting organic waste from high-rise buildings (see section 6.3.3.1). This appeared to be the most challenging aspect in Wageningen, for which a solid strategy has yet to be formulated. Although Rike van de Wiel (personal communication, March 13, 2014) expressed there is no current connection with the VA, it might prove beneficial for Wageningen to actively engage with this party by delivering input and keeping updated on their findings. Especially since Wageningen is still in a flexible piloting phase.

Whilst the activities and developments in the solid waste community are beneficial to P reuse, one finding of myself and Eckhardt (2014) is that P as a single nutrient, is not so much a topic in the solid waste community. This is confirmed by the SNA results of Eckhardt (ibid.) that show little connection between the actors in the solid waste community and remaining actors in the P network. This disengagement does not need to pose a problem in practice, when looking at the larger goal of closing the loop on P. With the market forces driving the collection and high-value application of organic waste, the associated P is in fact currently reused. Simultaneously, one could argue that P is a topic that touches upon various sectors (food chain, WW, MSW) and it is therefore relevant to have communication and collaboration between these sectors to facilitate even more reuse and recycling of P (ibid.). Especially since one can question whether the increased recognition of value in organic waste will automatically lead to P reuse and recycling in the future. For instance, producing chemicals (to serve as biodiesel) and pharmaceuticals from organic waste might be of high-value (See section 6.3.3.1.), but what happens to P in this process? After all, P is a resource that should not be reused or recycled only once, but ought to remain in a continuous cycle where it can always be accessed to re-enter the human food system. Finally, a stronger inclusion of the solid waste sector would also provide a more complete story of P and balance some of the current emphasis of the P issue on WW.

Beyond the increased recognition of value in organic waste, the general trend is to view *all* waste as a potential resource. This is an important development, because besides P that is the focus of this thesis, there are also many other valuable (micro) nutrients (for instance zinc) present in waste streams. The term 'circular economy' has already been mentioned in section 6.3.3.1, and stresses the value of resources and the importance of maintaining this value for future purposes. An exploratory study by the Ellen MacArthur Foundation (2013) shows that a circular economy poses a big market potential. Here, Amsterdam is a leading example that has recently conducted research, together with Wageningen University, on what measures can be taken within the urban area, to achieve a circular economy (Reinhard et al., 2013). Wouter de Buck (personal communication, October 18, 2013) also argues that municipalities can make use of such trends and developments, as it allows framing their actions in a wider perspective and improves their image. With regard to P specifically, he points out that the Netherlands is a frontrunner on researching and implementing measures for P reuse and recycling. Moreover, the recent foundation of the Dutch Nutrient Platform (NP) and the European Sustainable Phosphorus Platform (ESPP) (see section 1.4) signals an increase in recognition of P issues on a national and supra-national scale. Wouter de Buck (ibid.) therefore stresses, that municipalities can make use of these developments and become a frontrunner themselves by taking action on this topic.

Besides market forces, current regulative forces also foster P reuse and recycling. An example of this is found in MSW. Following the principles of the circular economy, the state secretary of Infrastructure and Environment, Wilma Mansveld, has formulated stringent targets on separation at source of solid waste (see section 6.3.3.1) to ensure resources are no longer wasted (Mansveld, 2014).

7.3.2. Local context

Limitations

The most important limitations for the municipality to further P reuse and recycling are on the level of WW, where it experiences a limited capacity to impact the WW system. Harry Post (personal communication, March 13, 2014), project manager sewerage and water management at the municipality of Wageningen, explained that much of the time, money and effort is directed to simply maintaining the current system. This operational focus leaves little room for innovative thinking. Apart from this, the influence of the municipality with regard to devising the sewerage system within the urban borders appears to be minimal and is for a large part due the fact that the municipality has little to no influence on how land plots are being developed. Much of the potential for P reuse and recycling is determined by the chosen WW collection system. As this decision is made by the client and the real estate developer, it is beyond the influence of the municipality. The municipality also has little grip on the actions of real estate developers, as much of the land is owned by the WUR (see Appendix VI: Land owned by the WUR in and around Wageningen, the Netherlands), which prevents any say in to whom the land is sold to, and/or how it is being developed. The real estate development of land owned by the municipality itself is outsourced to private parties since Wageningen is a 'regie gemeente' (see section 6.3.1.2). Although this does not mean all is beyond influence, it does entail that the municipality is not the only and immediate consulting partner that can make decisions. The municipality of Barneveld, a nearby municipality of similar size, does take on its own real estate developing, which provides much more opportunities to influence the design and building process (Harry Post, personal communication, October 30, 2013). Moreover, the municipality also expressed it is more inclined to play a facilitative, supportive role than an enforcing role with regard to the implementation of alternative WW systems that could further P recycling (Harry Post, personal communication, March 17, 2014). The absence of actively taking initiative to further P recycling might also be due to the current WW system having large sunk costs and sufficient capacity (see section 6.3.1.2). This results in a lack of incentive for the municipality to implement alternatives (such as DESAR) from an economic point of view. In addition, the proposed alternative of separate collection of urine at events, showed to have very little effect on total P reuse and recycling. This finding is also expected to give little incentive to the municipality to take action independently. Therefore, especially with regard to P found in WW, collaboration on a regional scale is important for enhancing the feasibility.

In contrast to WW, enhancing P reuse via MSW management poses more opportunities, which are further elaborated on in the subchapter 'Opportunities' below. The most important limitations found in MSW are as follows: First, there is at present little to no grip on waste originating from the non-household sector. Second, there is a lack of knowledge on what could be the best strategy to enhance a higher organic waste separation rate in low- and high-rise buildings. However, the current pilot testing on waste collection methods is expected to mediate this lack of knowledge to a certain extent.

A final limitation to further P reuse and recycling (valid for both WW and MSW), is the seemingly disconnectedness of the municipality: the SNA results of Eckhardt (2014) show that the municipality is very much detached from other actors in the network of P. The municipality, as part of the 'action community', turns out to be disengaged from the knowledge community, which is mostly represented by the WUR and other research institutions. This limits cutting edge knowledge from reaching the municipality that might be of value to enhance P reuse and recycling. Without the connections to the action community, no implementation of innovative ideas arising in the knowledge community can take place. As stressed by Eckhardt (ibid.), there is thus a need for bridging this gap in order to advance P reuse and recycling.

Opportunities

The low-hanging fruit for the municipality of Wageningen to act upon in the near future mostly appear to be on the level of MSW. This is mainly due to its grip on collection and treatment of MSW originating from households – which accounts for more than half of all P load found in MSW (11.7 t P/yr versus 10.6 t P/yr from non-households). The responsibility for the waste collection service of all households gives the municipality an opportunity to compel citizens into separating their waste to a certain extent[131]. With 78 % of food waste still disposed of in the mixed waste (see section 6.3.3.1), MSW also presents an opportunity for the municipality to improve its management. In practice, achieving higher separation levels of organic waste showed to be challenging (see section 6.3.4.2). Yet, research within the MSW community on enhancing organic waste collection (and the associated P) is still ongoing, or needs to be further trialled and tested (Gijs Langeveld, personal communication, March 19, 2014). The municipality of Wageningen could therefore benefit from actively connecting to, and engaging with, parties that are undertaking similar activities - such as nearby (and similar) municipalities[132] or the business association VA - to tap into knowledge on formulating the most optimal strategy for achieving even higher organic waste collection levels. Examples of relevant knowledge for the municipality of Wageningen are the following: First and foremost, the current research being conducted by VA to compare best practices on tackling the challenge of high-rise that is also experienced in Wageningen (see section 6.3.3). In addition, there is also a growing interest in understanding consumer behaviour which is known to be an important component in waste separation (Gijs Langeveld, personal communication, March 19, 2014, Rike van de Wiel, personal communication, March 13, 2014). Gijs Langeveld (personal communication, March 19, 2014) points out that the 4 largest cities in the Netherlands (Den Haag, Utrecht, Amsterdam, Rotterdam) aim to conduct research into the behaviour of the consumer. Also the municipality of Wageningen is already undertaking efforts to actively approach citizens in order to understand their motivations and

[131] Despite this influence, municipalities are dependent on citizens to separate their waste at source. The enthusiasm and willingness for consumers to separate their kitchen waste (and the associated amount of P) has dropped since the 1990's from around 80 % to approximately 65 % (Vereniging Afvalbedrijven, 2013a).
[132] The municipality of Wageningen is already aware of this and willing to undertake such efforts: The nearby municipality of Veenendaal is currently doing trials with diftar. The obtained results will also be evaluated by the municipality of Wageningen. If successful, Wageningen might be willing to reconsider implementation of diftar (Rike van de Wiel, personal communication, March 21, 2014).

behaviour. The municipality of Wageningen could thus take advantage of efforts undertaken elsewhere that might be of interest for implementation themselves.

Furthermore, pets and the collection of pet excreta in specific, clearly forms an opportunity from the perspective of P. The municipality could thus even more stimulate the disposal of pet excreta via the organic waste stream. Due to the importance of dog excreta (see section 7.2), the municipality might also conduct research on possibilities for collecting (more) dog excreta and ensuring proper waste treatment of such, e.g. composting this waste stream, to further P reuse or recycling[133].

Apart from MSW originating from households, also non-households present an opportunity. ACV group, the municipal waste collection company of which the municipality is a shareholder (ACV groep, 2014), also offers services for company waste collection. Via ACV group the municipality can thus expand its influence from merely households to actively engaging businesses to enhance separation of organic waste. The municipality is currently not actively focusing on company waste, as it is not obliged to collect this waste. With regard to company waste, the municipality could also make more use of enforcement measures by taking up obligations in the required environmental permit (Rike van de Wiel, personal communication, March 13, 2014).

On the level of WW, the municipality is far more limited in opportunities for realising P recycling and it appeared a regional approach is necessary. Not only to upscale results, divide costs and responsibility, but also to engage with the water boards that currently have direct responsibility over wastewater treatment. An opportunity to put P recycling into practice might therefore be the regional Platform Water Vallei en Eem (PWVE) (see section 6.3.1.2) that could initiate, coordinate and organise the proposed option of collecting urine at events in the entire region (Eckhardt, 2014) and the PWVE could actively be used for discussing and researching other (local) P recycling options. Also the already existing regional ties in the form of 'Regio FoodValley' are expected to be beneficial for collaboration among the various surrounding municipalities (see Chapter 5). In addition, collecting urine from events would also have an intrinsic value in itself for education purposes towards the public and for setting an example. Contrary to the solid waste community where P is not given specific attention, in the WW sector there is. Here P is an important topic as a single nutrient[134]. The single focus is beneficial for profiling and communicating towards the public. Chapter 4 already illustrates that P is an important issue that requires political attention. This study shows it is increasingly becoming a topic on urban[135], national[136], and more recently, EU level with the ESPP (2014). Taking a frontrunner, exemplary position might also be valuable for the image of the municipality and could be a start for more initiatives on P reuse and recycling. Wageningen that already known for its leading environmental sciences and having an agricultural backdrop (see Chapter 5), would make nutrient recovery a suitable topic to identify with. It could even be framed in the context of actively partaking in a circular economy, something Amsterdam is currently doing

[133] Due to time constraints, it was not possible in this thesis to research in depth how much dog excreta at present, is annually collected via waste bins or what the exact disposal method is (see Appendix I: Data collection per subsector of P output for sources used and assumptions/decisions made on calculations of pet excreta). It might thus be possible that P in dog excreta collected via waste bins is already reused or recycled.

[134] however, as expressed previously in this chapter, there are many more valuable micronutrients present such as copper and zinc that also ought to be given attention such as copper, zinc etc..

[135] The urban level is illustrated by the initiative of the conference called "Circular Economy in Cities: Focus on Phosphorus" that took place in Berlin, on January 21, 2014 : (Royal Dutch Embassy, 2014)

[136] National level is represented by the NP (Nutrient Platform, 2014)

(Reinhard et al., 2013). This context would present a more holistic approach in which actions concerning MSW can also be framed. The vacuum toilets that the municipality is aiming to install (see 6.2.1) could also serve as an important inspirational example for other parties involved with developing real estate[137]. As explained in section 6.2.1, the (economic) feasibility of P recovery and recycling all starts with a more concentrated waste stream. Installing vacuum toilets is an important first step to be ready for future transition (Everard, 2013) - albeit decentralized sanitation systems or P recovery and recycling at the WWTP. Both situations would benefit from a more concentrated WW stream. Especially with the increased concern over micro pollutants of which the majority is contained in urine (Maurer et al., 2006), a more concentrated stream of WW (which is far less diluted by water) would be preferred for efficient WW management (ibid.). One important side note to the possibilities of the municipality taking on an exemplary frontrunner position: Wageningen could only be acknowledged as such, if the actions taken by the municipality become known to, and can be duplicated by, other (relevant) parties, e.g. real-estate developers, businesses and other municipalities. This would be another argument for better connection of the municipality to other actors in the P network and/or make more use of its current ties to reach out to the public or private parties to follow the example.

7.4. Implications

What are the implications of all findings for municipality and for the larger context?

7.4.1. Municipality of Wageningen

For the municipality of Wageningen, these results aid in understanding its current performance and future possibilities for P reuse and recycling that is influenced by its waste management system. It also gives a rough estimation of the hotspots in P losses that require attention and what appear to be low-hanging fruits for improving P reuse and recycling. From a municipal perspective the results show that most of the limitations on a national and local level seem to be experienced on the level of WW. In contrast, most of the short-term opportunities (low-hanging fruit) are found in MSW management. For successfully implementing measures with regard to both WW and MSW, it showed that a more connective and engaging approach towards other actors and organisations is expected to be beneficial. This could take shape in regional collaboration and exchange, engaging with national organisations such as the VA, or with specific actors in the knowledge community to further the amount of P reuse and recycling in future.

7.4.2. Larger context

Understanding how the findings of Wageningen relate to the larger context consists of two aspects addressed below: first, placing the findings in the larger debate of the potential difference between small municipalities, such as Wageningen, and the larger municipalities such as Amsterdam or Rotterdam (in the case of the Netherlands). Second, the potential contribution of urban areas with regard to the larger (national and global) P issues is addressed.

Small vs larger municipalities

Eckhardt (2014) formulated 4 roles that a municipality in *general* could take on to stimulate P reuse and recycling: (i) a facilitative role, (ii) a regulative role, (iii) an executive role, (iv) an educative role

[137] The study of the possibilities for a closed loop practice of P in Amsterdam, explains businesses are willing to adopt innovative sanitation systems, such as urine separating toilets .(Reinhard et al., 2013)

(for more information the definition of these roles see (Eckhardt, 2014)). What do these roles distinctively mean when considering the differences between small and large municipalities?

For smaller municipalities, such as Wageningen, a facilitative role is more challenging. Eckhardt (2014) points to the municipality of Amsterdam as an example that initiates, stimulates and brings parties together in order to obtain a closed loop practice of P. In contrast, smaller municipalities such as Wageningen, have much less power, money and capacity to initiate and organize innovative projects (Harry Post, personal communication, March 13, 2014). Small municipalities thus appear less likely to take on a frontrunner position themselves.

Both small and larger municipalities have the capacity to take on a regulative role. However, as illustrated in section 6.3.1.2, the municipality of Wageningen preferred changes in the waste management system to be a product of collaboration instead of enforcement when dealing with private parties. Within Wageningen, the companies - and specifically the WUR - have much influence. This situation illustrates that smaller municipalities might experience less freedom in dictating and enforcing their policies – even if they have the formal capacity to do so.

Having merely an executive role is likely for smaller municipalities, as they lack the means to also facilitate and initiate. When outsourcing the initiative to a third party, potentially in the form of a collaborative platform, small municipalities ought to be wary of simply implementing measures that appeared to have worked in other contexts. The case of diftar shows that local context definitely matters. Whilst the municipalities that successfully implemented diftar are in fact small, and one could say 'similar' to Wageningen due to their size, the inhabitants and building types are completely different. This also strengthens the argument made by Hodson and Marvin (2009), to explore various contexts that are characterised by different capabilities and opportunities – not only based on size (larger and smaller municipalities), but perhaps also based on population and building type.

An educative role, for example urine collection at events, has shown to be possible in smaller municipalities when there is regional collaboration to upscale the results and divide the responsibilities and associated costs. By taking on an educative role the municipality can also set an example (Eckhardt, 2014). As smaller municipalities lack the capacity to initiate and facilitate, they are not the bridging actors between various organisations in order to achieve optimal P reuse and recycling. In contrast, the SNA results show the municipality of Wageningen as grossly disconnected from the P network (Eckhardt, 2014). Being a smaller municipality might thus limit their reach. Taking on an exemplary role only has effect if other (relevant) parties are sufficiently aware of the initiative (see 7.3.2). Therefore, in order to successfully take on an exemplary and educative role, a higher connectivity and engagement with other actors is vital. Again, uniting of smaller municipalities in a collaborative regional approach is expected to be supportive in achieving this.

Urban areas in relation to larger P issues

The question still remains how the actions concerning P, taken on an urban level, relate to the P issues at a national and global level. In discussing this, the perspective of a local, municipal government is still adhered. The larger issues at hand addressed below are underlined in the text. More information on these issues is found in Chapter 4.

Some of the identified P issues on a global level can be grouped together, as all are positively affected by P reuse and recycling measures implemented on an urban level. These are as follows: geopolitical dependence, potential (economic) scarcity, general losses and an increase in phosphorus demand. Although the P flows from an urban area are smaller in comparison to flows related to agriculture, cities should not be neglected when considering that the results of this thesis and research on similar SFA studies[138] show that most of the P in urban areas is eventually lost. This clearly demonstrates much still needs to be done to achieve a more closed loop practice of P in which cities might not play the leading role, but definitely have a part. Any actions taken on the urban level to foster P reuse and recycling could thus contribute to achieving a stronger geopolitical independence, avoid scarcity and losses and meet rising demands.

Unfortunately, the urban areas have very limited influence and effect on the issue of pollution and contamination due to heavy metals in mineral fertilisers. In a sense, by diverting waste streams to produce products such as compost and struvite and aiming to ensure these are of high-quality – a municipality could contribute to the production of alternatives to mineral fertiliser on the market. A municipality however cannot impose bans on imports or restrict certain contaminants through elevating required standards. Here, the urban areas are dependent on the governance of the national or even EU level.

Taking actions on an urban level, can only have limited and indirect effect on the specific issue of eutrophication and saturated P soils that the Netherlands deals with. Cities cannot reduce the amount of P currently in the soils, yet they can contribute to the production of compost. With compost having soil conditioning properties, leakage of P towards groundwater and surface water is to a certain extent avoided. A municipality cannot actually contribute to the recovery and recycling of P found in WW, as this is currently being diverted towards centralised WWTP. In the Netherlands, results show that the WWTPs fall under the responsibility of the water boards. When more decentralised systems might appear in future, these roles and responsibilities for ensuring P recovery and recycling from WW might change.

Apart from being able to *specifically* address the afore-mentioned P issues, urban areas have one quality that has a more general, yet potentially very valuable, impact: cities are hotspots for people, which gives municipalities the power to raise awareness and educate. With most of the human population living in concentrated urban areas (WHO, 2014), this presents the opportunity for enormous reach. Municipalities taking on an educative role can contribute to have people not only understand P issues in general, but also their own connectivity and responsibility in these issues. After all, despite much of the P flows being 'owned' by the rural sector, it is the cities and its inhabitants that are responsible for the demand for most of the (agriculturally produced) products containing P. This demand is in turn responsible for the current agricultural practices and its (often long) supply chains. The latter also increases chances for P losses at numerous stages (Cordell, 2010) of which an overview was presented in chapter 4. Education on the P topic could inspire people to take action on a local level (separating organic waste for example) and demand changes on a national or even supra-national level. This is why it is vital that the story of P is not only gaining momentum on national or EU-level, but also on the more local, urban level.

[138] (Chowdhury et al., 2014; Cordell et al., 2012; Kalmykova et al., 2012)

7.5. Methodology

7.5.1. Chosen case study and system boundaries

When taking a smaller municipality as a case study, one is prone to find that the waste treatment is usually not within administrative borders. Strictly adhering to these borders would prevent necessary insight into the actual (eventual) destination of P. Therefore, it proved beneficial to include specific processes beyond these administrative borders. Moreover, it visually illustrates that cities are not islands, but very much connected to and dependent on the hinterland and beyond. Especially for smaller cities, the accumulation of the P (and thereby the so-called 'hotspots' (see section 1.2) do not occur in the city itself (apart from any potential stocks), but at the waste treatment facility located outside the city borders and finally diffuse everywhere in infrastructure and waterways.

In general, the choice for system boundaries presented a difficulty for comparison with other similar SFA studies. One example of this, is the study conducted by Tangsubkul (2005) in Sydney. Here, the larger region was considered in the study - including the agricultural areas. This was not included in the SFA of Wageningen, which leads to different outcomes in P input, stock and output. In addition, the functional demarcation differed from other SFA studies. This thesis was limited to P found in food consumed by humans and pets only – as food represented the most significant urban P flow. Some SFA studies did not even consider pet food, whilst other SFA studies included all products containing P. What also made comparison with other SFA studies challenging was the chosen case-study. Selecting a relatively small municipality was deliberate, as this represented a gap in current research (see section 1.2). Yet, most of the current SFA studies regarding P on an urban level concerned large cities (Sydney, Gothenburg, Phoenix, Beijing etc.) The SFA study on Linköping, Sweden, is the closest in size to Wageningen, with around 150.000 inhabitants (Municipality of Linköping, 2013). This is still a significant difference in size, affecting the ability to make a solid comparison.

It would have been helpful if these differences in other SFA studies (and their similarities) were more carefully taken into account from the start. Potentially one (or perhaps even a few SFA studies) could have been chosen as an example to be modelled after by taking similar system boundaries and a comparable case-study. This would have allowed better comparison between the outcomes for validating or cross-checking results.

7.5.2. Data

Availability

In general, the availability of data obtained in this study can be considered reasonably good. With respect to qualitative data: all people we aimed to interview were very cooperative and willing to supply information and gather additional within their organisation if asked for. However, personal communication via email sometimes proved more challenging, which is addressed further below under '*Accessibility*'. Also a fair amount of the required quantitative data for assessing the baseline could be acquired - especially data regarding WW. Here statistics and research on dietary intake, as well measurements from the WWTP, were considered fairly solid. P destined for MSW did present a challenge - especially the non-household sector. This proved to be the largest data gap. Besides the WUR, which was exceptionally cooperative in providing numbers on waste, no specific data could be obtained. This was not only because certain actors weren't willing to cooperate, but mostly due to a lack of time within the scope of this thesis to contact actors in the specific sectors individually, in order to gather the required information. The lack of time resulted in having to rely on earlier studies and reports on waste in the non-household sector (company waste, supermarket waste etc.). These reports were very limited and sometimes not very specific with regard to food waste, its composition and quantity. Even if there would have been time to contact specific actors, it can be questioned whether information would have been provided. After all, the non-household sector is marked by confidentiality – certainly when the required data concerns waste. This lack of data (and its reliability) appears to be a common problem, as it is also signalled by Cordell et al. (2012) in other SFA studies.

There was also limited to no data available for estimating the effects of the formulated strategy on the amount of P being (additionally) diverted to organic waste. This was because no information was known on how much of the organic waste additionally collected, represented food waste. Following this, it was not possible to know the associated amount of P in the additionally collected organic waste. Whenever the required data was not available, if possible, it was compensated for by use of other sources. Nevertheless, this meant making assumptions which impacts the certainty of the results. Uncertainty of data is further discussed below.

Accessibility

A thesis project is often an iterative process, where the gathering of certain data and insights sometimes leads to additional questions or requests for data that could not be foreseen. With in-depth interviews, one has the possibility to immediately act on these thoughts and subsequently alter or add some topics for discussion. People that were interviewed were also found to respond quickly to additional emails and were very willing to provide further information when necessary. With regard to personal communication via email, this was experienced as more arduous to obtain the requested information. First, it was sometimes more difficult to properly formulate questions in order to obtain the necessary data. Via email there is no conversation in which more context or explanation can be given immediately - to further elaborate or express what is meant by the questions. Furthermore, actors that were contacted through email were less prone to respond in general, which took quite come effort in sending reminders via email or contacting them by phone. In some cases, no response was given at all or it stopped at some point, which prevented gathering the necessary data. However, when the person contacted through email was introduced by someone that was previously interviewed (which was the case with the WUR that provided further contacts) there was a much more active response and cooperation. This illustrates the additional value of in-depth interviews, as an interviewee is more prone to further assist in your research and can introduce you to valuable contacts. Thereby providing an easier access to the required information.

Uncertainty

There is a fair amount of uncertainty in the collected quantitative data, which impacts the final result. First, the lack of data required the use of various sources from different years. This impacts the accuracy. One example is that the domestic input is taken from the year 2011, whilst the chosen base year of the SFA is 2012. Many of the sources concerning the output, of which WW being the most prominent, are from 2012.

Moreover, there was known uncertainty in the data itself. One prime example is the domestic P supply from food. This number already has a fairly large dispersion in itself[139]. As explained in section 6.2.2.3 and 7.2, the P input determines the amount of P assigned to the residual flow (<F41>) (see SFA of current situation, non-households, in section 6.2.2.3). The size of the residual flow is thus by definition highly uncertain and also its destination could not be verified. Being a relatively large flow, it does affect the image of the results presented.

Another prominent aspect was the need for multiple sources of data to calculate certain flows. As explained in Chapter 3, P quantities found in MSW could only be calculated by taking various steps (see section 3.5.1). This reliance on multiple sources of data results in more variables and thereby increasing the uncertainty of the results and the amount currently marked as P reuse.

In addition, some data could not be obtained at all, or was not specific enough. Most of these issues were encountered in the calculation of P found in food waste and especially within the non-household sector. Often the composition of food waste was unclear or defined in such rough categories, that the determination of the associated P - based on P contents - had to be based on assumptions. Determining for instance, whether or not to include coffee residue, bones of fish and meat, has a high effect on the amount of P present in the waste (for more information on amount of P in food waste, see Grembecka et al., 2007; INRA and AFZ, 2004; RIVM, 2011a). These assumptions can thus have significant consequences on the entire outcome of calculated flows. Here, it not only concerns assumptions made on quantity, but also on destination of flows. One crucial example of this is the residual flow (<F41>). Due to a lack of knowledge, it is assumed that most (if not all) ends up in the mixed waste stream (see section 6.2.2.3). With the residual flow being fairly large (compared to other flows in the non-household sector) and the destination assumed to be incineration, this highly affects the P reuse performance of the non-household sector in Wageningen. Another important example of the uncertainty in the destination is pet food. Here, an assumption had to be made on the amount of P ending up on land, in mixed or organic waste (see Appendix I: Data collection per subsector of P output). If one alters the current assumptions, it could entirely change the final result. For instance, if one assumes less P from pets ends up on land, this impacts the total amount of P found in MSW. The overall outcome would then be relatively more P in MSW than in WW. Also the current assumption concerning the amount of P from pets diverted to organic waste, affects the total performance of Wageningen on P reuse and recycling. In general, all these assumptions are of course made with the utmost possible accuracy, yet its contribution on the overall uncertainty is an undeniable fact.

Where uncertainty in the obtained data and results can often be cross-checked with results obtained from similar studies, this was difficult with regard to this thesis. To begin with, there are relatively few SFA studies on an urban scale, which is illustrated by two recent reviews (Chowdhury et al., 2014; Cordell et al., 2012). Furthermore, the conditions and context of the cities in question are quite distinct from one another and thus difficult to compare – especially to Wageningen. For instance, the SFA of Beijing (Qiao et al., 2011) is a prime example that has an entirely different context with regard to waste management, legislation etc. that is far removed from anything applied in the Netherlands.

[139] The initial domestic P input from food supply is based on the Dutch domestic P supply from food. The latter is estimated at 17.5 Mkg P with a large dispersion of 3.3 Mkg (Bert Smit, personal communication, November 27, 2013, publication in preparation).

Also the sheer sizes of cities are distinctly different from Wageningen. Furthermore, as explained previously, the defined system boundaries between various SFAs are not the same.

Finally, time constraints also contributed to uncertainty in some respect, as this prevented deeper or more thorough searches that could have further minimised uncertainty. This goes for quantitative as well as qualitative data. Especially for the latter, validating opinions and remarks made with other sources is important, yet time constraints did not always allow such thorough research.

7.5.3. Data preparation and analysis

The SFA methodology and its required steps have proven to be a useful tool to gather quantitative data and analyse the amount of P reused and recycled on an urban level. First and foremost, it helps in determining clear boundaries and offering a guideline for the necessary information to be obtained. The forthcoming SFA, devised by the supporting software of STAN, captures all acquired information in one encompassing figure. An SFA showed able to pinpoint current P losses, which are actually opportunities to further P reuse and recycling. The SFA provides the basis for action, as it gives useful insight into which flows require attention and which flows make the most significant impact. Moreover, this study was able to demonstrate the potential impact of future alternatives by use of SFA. An SFA can thus be used for analysis and the formulation of conclusions in one quick, visual glance. In this respect, STAN has shown to be specifically helpful: the line thickness is determined by the size of the flow, which immediately captures attention to the most important flows. Also the option of colour use aids in understanding the figure. The ability to create subsystems limits the complexity whilst still offering further insight into subdivisions. Also the possibility in STAN for inserting uncertainty of data is valuable, since this has shown to be unavoidable and needs to be taken into account when presenting SFA results. It nuances the data and can help a municipality to focus its measures and have an understanding of where more research is required. Whilst STAN helps in visual understanding, it is not always sufficient to get (all) important conclusions across in one glance. Use of supportive figures such as pie charts for clarification and illustrating (sub)conclusions have shown to be very useful.

A limitation of the constructed SFA is that it is a static picture. The obtained results on certain flows of the current baseline are expected to be obsolete in the nearby future. Especially when considering the current developments in the field of MSW with its pilots and future strategies. Nevertheless, the SFA does provide an overall insight into waste management practices and its effect on P. This can be used as a starting point from which to formulate policies or carry out a longitudinal study that would allow measuring the effect of policy decisions on the amount of P reused and recycled. Longitudinal SFA studies on P are identified by Chowdhury et al. (2014) as a research gap. It is explained that - with the exception of the SFA study on the city of Linköping, Sweden – none of the SFA studies take a long view perspective. Most SFA studies on city scale comprise only one year, which does not allow making any conclusions about the impact of policies on P flows.

Another important aspect to consider when using SFA methodology is that it is quite easily prone to errors. Since an SFA is on the level of a substance, a lot of data is required, as well as making conversions and calculations to obtain necessary numbers. This obviously increases chances for inserting wrong numbers by accident, or making calculation errors – affecting the eventual result. Therefore, the value of maintaining a clear overview in excel sheets (which is still subject to mistakes, yet can more easily be checked) cannot be underestimated to minimise such errors.

A final shortcoming of SFA is that it cannot show to what extent certain flows can be diverted in practice. Neither does it reveal much of the *limitations* that might be experienced when aiming to further P reuse and recycling. This limited and quantitative nature of SFA is also stressed by Cordell et al. (2012). For this, qualitative data on the context proved essential and complimentary.

With regard to the analysis of qualitative data, making clear thematic comparison sometimes presented a challenge. This was partly because the interviews were conducted together with my colleague Timo Eckhardt. Although our different emphasis on the same case study did result in gaining a more comprehensive and holistic view on the issues at hand, the interviewees were also from very different backgrounds and expertise. Therefore, some topics did not always apply for any interviewee and could thus not be systematically compared. One could argue it would have been perhaps beneficial to have focused more on people specifically related to the chosen perspective of technology and infrastructure for this thesis. This might have made comparison and cross validation of topics easier and could have given more depth.

Overall, the acquired knowledge, combined with insights from Eckhardt (2014) provides a more holistic perspective on the limitations and opportunities for a small municipality such as Wageningen to advance reuse and recycling of P food flows. Yet, what do the findings of this case-study imply for other municipalities?

7.5.4. Applicability of findings to similar case studies

Overall, it is assumed that these findings are *mostly* applicable to similar, small municipalities within the Netherlands as they would share the same basic conditions. Cities in other countries operate within a different context (no P saturated soils for example) and have other legislation and governance.

Nevertheless, some key findings from the baseline are expected to be applicable to urban areas in general. The first is the importance of P related to pet consumption. As explained in section 7.2 earlier, pet food is presumed to be an underestimated flow in urban SFA studies regarding P – with an emphasis on small municipalities. The considerable amount of space and rural hinterland that small municipalities are associated with is assumed to result in similar outcomes. A second finding expected to be valid in many other urban areas is the importance of MSW with regard to P flows. Although an almost equal division of P found in WW and MSW might not always be the case, the significance of both waste streams is clearly illustrated and verified in the study conducted by Kalmykova et al. (2012).

The findings regarding alternative strategies are much dictated by the national context that stimulate or constrain options for P reuse and recycling. For instance, the WW treatment falling under the responsibility of the water boards and is thus beyond influence of a municipality. Therefore, these findings are expected to be applicable in the Netherlands only. One example from the local level that is interesting for other Dutch municipalities is the effect of being a 'regie gemeente', which showed to impact the capabilities of the municipality to act or influence. Furthermore, the identified value of taking a more regional approach and investing in connections with other actors is expected to be useful for small municipalities to enhance P reuse and recycling practices.

There are also some results obtained in this thesis that are quite specific to Wageningen. An example is the WWTP and its lack of incentive for P recovery and recycling, which seems to be in contrast with other wastewater treatment plants (WWTP) in the Netherlands. After all, section 6.3.1.1 explained there is an increasing shift from a pollution perspective (eutrophication) that requires merely removal of P, towards a resource perspective of P (and nutrients in general) that drive recovery and recycling of P from WW[140]. The water board Vallei and Veluwe (also responsible for the WWTP in Renkum that treats the WW from Wageningen) is working on innovations to realise P recovery and recycling at the WWTPs in the municipalities of Apeldoorn, Amersfoort and potentially Ede in future. Despite this trend and ambition, no P recovery and recycling from WW originating from Wageningen is expected to take place (for the time being) (see section 6.3.1.1) Thereby, illustrating the chosen case-study is quite exceptional and will be even more so in future if the WWTP in Renkum does not participate in the ongoing trend of resource recovery. Yet, simultaneously one might argue that this lack of P recycling is also applicable to other smaller cities - now and in the near future. After all, the current trend towards resource recovery and recycling requires investments to be made. These investments are likely to be first and foremost made at WWTPs that are fairly large and/or important. Many of the smaller cities might be connected to more small scale, less significant WWTPs that will continue to merely *remove* P from WW in order to comply with imposed effluent standards.

Finally, an important question to ask oneself when aiming to apply these findings to other case studies is whether conditions are sufficiently similar. The comparison with previous SFA studies already show that urban areas are often very specific and difficult to compare, as this scale is more detailed than a national or perhaps regional SFA. As explained before, it is not merely the size of a city that matters. Diftar was an interesting example in this, for which its feasibility and value was not yet determined for Wageningen, whilst municipalities of similar size did implement diftar. It is clearly also important to consider the population 'types' that inhabit the city, the businesses that are present or potential industry that might be relevant. Even the building type is important, because this determines the ease of separating MSW, which in turn impacts the amount of P reused or recycled (high-rise presented a big challenge). All these variables and beyond, will affect the outcome of the SFA and determine the limitations and opportunities for increasing P reuse and recycling in a case study.

7.6. Conclusion

Whilst this study experienced some lack of data - especially regarding P in MSW - as well as issues of uncertainty that need to be considered when interpreting the data, there are some clear findings. First, this chapter illustrated the importance of considering P related to pets (especially in the context of the Netherlands) and estimated that it has been most likely an underestimated or neglected flow in similar SFA studies. In addition, this thesis showed the significance of MSW in P management and thus it is argued that the current emphasis on WW only, ought to be revised. Furthermore, it is found that not all P output (can be) deliberately managed, since most of cat and dog excreta is discharged uncontrolled and diffuse on land. Moreover, such uncontrolled discharge might be harmful,

[140] Rinus van der Molen (personal communication, October 16, 2013) explains that the water boards have made a long term agreement with AgentschapNL (which is now part of the Rijksdienst voor Ondernemend Nederland[140]); a so-called 'MJA3 (meerjarenafspraak)'. This agreement focuses on 3 aspects: (i) process-efficiency and (ii) use of sustainable energy as well as (iii) chain efficiency, which includes resource recovery.

depending on the local context. Therefore, this flow has found to be an opportunity for the municipality to further research on how to divert this waste to the waste management system. Overall, it is found that it is mostly MSW that presents the strongest opportunities for the municipality to act upon in the near future, in comparison with WW. This is mostly due to a combination of (i) the scope of influence on the waste management system and (ii) the incentive to alter the current system in favour of P reuse and recycling. Yet, improving P reuse and recycling through infrastructure can support image building of a city or region and set an example. In doing so, this might indirectly stimulate the amount of P reused and recycled. Moreover, the municipality can build more capacity to implement (appropriate) infrastructural alternatives if it enhances its connectedness to other relevant actors. Especially for small cities such as Wageningen, that might not have the same abilities in comparison to larger cities. Overall, it is stated that urban areas definitely have a role (and responsibility) to further P reuse and recycling with 94 % of the P still being lost. In doing so, urban areas can contribute to mediate some of the global concerns in a direct or indirect way. As an important finalising note, the applicability of these findings to other case studies is much determined by system boundaries chosen.

8. Conclusions and recommendations

8.1. Introduction

This chapter concludes all findings of this research by answering all sub-research questions and the main research question of this thesis. Finally, some recommendations are made for future research, based on the findings and experiences gained from conducting this study as well as findings from literature, to advance a closed loop of phosphorus (P).

8.2. Conclusions

The first sub-research question (Q1) was: *What are the infrastructural features of the current waste management system that shape the phosphorus food flows of Wageningen, the Netherlands?*

The waste management system that shapes the P food flow can be divided into wastewater (WW) and municipal solid waste (MSW). The research showed that all domestic WW, which is the most important source of consumed P (see Q2 below), is handled through a centralised collection, transportation and treatment system. As commonly practiced in the Netherlands, the municipality is responsible for collection and transport and the water boards for treatment of the WW. This is contrary to the management of MSW, which contains an almost equal fraction of P as WW (see Q2). Here, many different actors are involved that shape the P flows. With regard to MSW, the municipality is responsible for the collection, transport and treatment of household waste and offers the option of separate organic (and thus food) waste collection. Companies decide themselves which waste handling company is contracted and whether or not organic waste is separately collected. For both WW and MSW, the treatment takes place outside the administrative borders of the municipality.

<u>Concluding: The P food flows are shaped by WW and MSW management. The infrastructural features of the former are centralised, where the municipality is responsible of collection and transport of *all* WW. The latter system is decentralised, where the municipality is responsible for *household* waste collection, transport and treatment, and offers separate organic waste collection.</u>

The second sub-research question (Q2) was: *What is the current performance on reuse and recycling of phosphorus food flows of Wageningen, the Netherlands?*

Assessing the destination of P (reuse, recycling or lost) meant acquiring knowledge on which waste stream it was diverted to, and how this waste stream was eventually treated. A remarkable finding is that P appeared to be almost equally divided among WW and MSW, yet slightly in favour of WW. Whilst the findings are succumbed by a fair amount of uncertainty (which mainly concerned the P found in MSW) the following findings with regard to the performance can be stated: Of total input 51.2 t P/yr, 94 % was lost. This loss occurred mostly via WW and MSW, but also as pet excreta ending up on land, which accounted for 12 % of the total P input. The P found in WW (22.8 t P/yr) showed to be unfortunately all lost, as there is no P recovery and recycling taking place at the WW treatment plant. Instead, P ended up partly in the effluent and partly in the sludge that is eventually used as biofuel and thus incinerated. The remaining ashes containing P are not reused nore recycled, but sequestered in infrastructure such as roads and concrete. From the MSW stream (22.3 t P/yr), the P was reused in the form of compost if it was disposed of in the organic waste stream (3 t P/yr). The remaining P ending up in mixed waste was lost through incineration. Another impressive finding was the importance of P found in flows related to pets[141]. Apart from being a relatively large flow (24 % of total P input), most of it was not managed but uncontrolled discharged on land. Especially in the case of the Netherlands, with its eutrophication issues and saturated P soils, this is a relevant flow to take into account. On a more positive note, P from pets was also the major contributor to the total amount of P reused (80% of total P reuse) in the form of compost.

Concluding: the study shows no P recycling takes place, only P reuse (through compost via MSW), which together amounted to 6 % of the total P input.

The third sub-research question (Q3) was: *What infrastructural alternatives are feasible for the municipality that enhance the performance on reuse and recycling of phosphorus food flows of Wageningen, the Netherlands?*

From the perspective of the municipality, it can be concluded that alternatives concerning MSW have the most potential in the near future. On a national level, market and regulative forces push for more organic waste collection (resulting in P reuse). On a local level, research shows that the municipality can exercise influence on collection and treatment of MSW. It is fully responsible for household waste and through permits - as well as being a shareholder of the waste collection company ACV group - the municipality has a potential grip on waste from the non-household sector as well. The infrastructural alternatives are different for high- and low-rise. In general, a reverse collection system (with use of a pass for containers) as well as more frequent collection is suggested. The alternatives are only slight alterations to the current waste strategy to ensure (short-term) feasibility. In general, the study showed that more research within the MSW community is required for identifying successful options to enhance separation of organic waste (especially concerning high-rise buildings). Here, the municipality would benefit from connections to other actors and organisations that could supply appropriate knowledge.

The recovery and recycling of P from WW (in this thesis in the form of struvite) shows a different picture. On a national level, there is little incentive to stimulate actions for P recycling on a local scale: There is no demand for struvite in the Netherlands and P recycling in the form of struvite does not (yet) makes a sound business case. Moreover, there are strict national standards for P removal, but no regulative force demanding P recovery and recycling from WW. In addition, there are three important local inhibitions from a municipal perspective that limit the implementation of infrastructural alternatives: (i) ownership of land (much is privately owned by the WUR), (ii) ownership of activities (WW treatment is not a municipal responsibility and Wageningen outsources many activities such as real estate developing), and (iii) large sunk costs and sufficient capacity of current sewer system. There is thus a lack of incentive as well as a lack of influence. This is further affected by the limited capacity of a small municipality to take on innovative projects with regard to WW. The only potential alternative on the level of WW was found to be the collection of urine at events. Unfortunately, the scale of impact (see Q3) is found to be very little and together with a low capacity of the municipality to initiate such projects, it became clear that a regional approach is required to make this happen.

[141] This is most likely characteristic for small, more rural municipalities such as Wageningen, that house relatively more pets than larger cities.

Concluding: On the level of MSW, alternatives are only a slight alteration to the current strategy. On the level of WW, only separate collection of urine at events was found feasible at the short term. The feasibility of infrastructural alternatives and its implementation for improving P reuse and recycling, are determined by abilities on a local scale and developments taking place on a larger – regional, national or supranational - scale. Taking this into account, the low-hanging fruit mostly reside in MSW. Furthermore, the capacity to act can also be enlarged when strong connections with other actors are realised, that can either provide knowledge, or be a collaborating partner to share responsibilities and investments with. Especially in the case of smaller municipalities such as Wageningen, this proved to be of crucial importance.

The final sub-question (Q4) was: *What is the impact of the identified alternatives on the performance of reuse and recycling of phosphorus food flows of Wageningen, the Netherlands?*

Although this thesis could only present an estimation it became apparent that infrastructural alternatives of MSW had the highest impact on the performance of P reuse and recycling. This was mostly due to pet excreta being diverted to organic waste. Where usually the emphasis for achieving higher levels of organic waste is put on waste streams related to human consumption, this finding highlights the importance of considering waste from pets to further P reuse and recycling. Municipalities could thus more actively encourage citizens to dispose of pet excreta in the organic waste stream and potentially manage the bins for dog poo more sustainable by composting this waste flow. The contribution to P recycling on the level WW (via separate urine collection at events) was very little and can be marked as insignificant. The suggested alternative however, was not found to be entirely nugatory. Up scaling the urine collection initiative to a regional level in a collaborative project with other municipalities has value potential, as it goes beyond mere P recovery and recycling. It is also an opportunity to build image, educate the public on P issues and set an example for other public and private actors to follow. This illustrates that alternatives can have direct impact on P reuse and recycling, as well as a potential indirect effect.

Concluding: The combined effort of the suggested alternatives is not expected to have an enormous impact on the performance of reuse and recycling of P. Only about 1 t P/yr (2 % of P input) was estimated to be additionally diverted, of which most is P related to pets. Nevertheless, this thesis only touched upon the matter of alternative strategies and future research could prove different.

The combination of these sub-research questions ultimately bring us to the main research question of this thesis: ***What are urban infrastructural limitations and opportunities to enhance reuse and recycling of phosphorus food flows of Wageningen, the Netherlands?***

The ability of a municipality to alter the destination of urban P flows - by altering the urban infrastructure - has shown to be affected by various aspects. Both limitations and opportunities have shown to manifest itself on various geographical scales, where the urban is influenced by regional, national and supranational activities. The most important limitations and opportunities that have been identified throughout this research are as follows:

The study clearly showed that most of the potential for the municipality of Wageningen to advance P reuse and recycling, resides in the organic fraction of the MSW stream. On a local scale, this is mainly due to the fact that the destination of P (reuse or lost) found in MSW can be largely influenced by the municipality. Within MSW management, one distinct opportunity to foster P reuse is to ensure pet excreta is diverted to the organic waste stream. The limitations for altering the destination of P were mostly experienced on the level of WW. This is a centralised system where water boards hold the responsibility for WW treatment and subsequently determine whether P recycling takes place, which in this specific case was not practiced. Decentralised systems that could place the responsibility at the municipality proved (at present) not feasible. This was mostly due to a lack of incentive (large sunk costs current system) and a lack of influence. The latter was determined by insufficient ownership of land, and ownership of activities (outsourcing all activities). This was further aggravated by the inability of a small municipality such as Wageningen to initiate innovative projects regarding WW.

Apart from the local (in)capacities, it was also on a larger scale that MSW presents the strongest opportunities. This is due to the value potential of organic waste (in contrast to P recycled from WW in the form of struvite), as well as regulative forces that drive for higher separation rates. Thereby, an incentive (on a local level) is provided for implementing infrastructure that advances P reuse in the form of compost or a potential high value application such as larvae for animal feed. Where most SFA studies have focused on P found in WW, this thesis thus argues that MSW requires equal attention. Especially since almost half of all P from food flows is found in this waste stream. Furthermore, combined research showed that whilst the municipality is not strongly connected to potential relevant actors in the P network, this is of importance for building capacity to further P reuse and recycling on an infrastructural level. The degree of connectedness to other actors, platforms or organisations is a crucial opportunity – with a specific emphasis on a regional scale. Especially for a small municipality such as Wageningen, strengthening current ties and starting new collaboration forms, could strongly aid in the implementation of (appropriate) measures for P reuse and recycling. In addition, this thesis stressed that there are indirect opportunities for urban areas to further P reuse and recycling. By implementing infrastructure that stimulates P reuse and recycling, it can be an opportunity for setting an example and educating the public on the P issues at hand.

<u>Concluding: For Wageningen, the infrastructural opportunities to further P reuse and recycling are found in WW and MSW management, with a strong emphasis on the latter and specific attention for pet food flows. In both WW and MSW management, building capacity to implement appropriate measures for P reuse and recycling could be strongly aided by connecting to relevant actors for either knowledge or collaboration.</u>

8.3. Recommendations

This thesis only presents a small part of the answer to the larger question of how to manage P more sustainably, and what potential role urban areas could fulfil in doing so. Further research is required that might verify or debate the conclusions made in this thesis, as well as extend the knowledge and insights on how to close the loop on P. Below, some recommendations for further research are made.

Potential scenarios

First, more research on working out potential alternative scenarios and their expected impact would be valuable. Especially since the proposed alternatives did not result in a high impact. Assessing the baseline is the necessary first step, yet it naturally leads to questions on what might be potential alternatives. In this research, it was not possible to investigate all possible interventions in depth. Especially pet excreta would be interesting to research, seeing as this showed to be an important flow and most of the P ends up on land uncontrolled. How could this best be tackled to ensure a form of controlled P reuse or recycling? Moreover, this thesis was restricted to alternative options concerning infrastructure, but one might also consider policy interventions on diet changes, or the effect of creating shorter supply chains of products containing P with less stages in between that could result in less losses.

Data availability and reporting

Another important issue that came forth during this research was the absence of sufficient (quality) data on P in MSW flows - especially with regard to the non-household sector. This resulted in having to make assumptions, which increases the level of uncertainty of this study. This issue is also identified by Cordell et al. (2012) who mention there is a need for more standardised and improved reporting. In order to improve this, there might be a major role for institutions such as 'Statistics Netherlands' (in Dutch known as CBS). Also from the non-household sector, it might be possible for CBS to acquire certain 'big' data in an anonymous fashion. This would allow for a more accurate and reliable source of information yet prevents the revealing of specific, confidential company information.

In order to set up an improved data and reporting scheme, it is also necessary to more clearly understand what exactly *are* the main gaps of knowledge (for instance, the non-household sector is still a very broad category). Here a potential review of current SFA studies could provide assistance in understanding more specifically what target sectors need to be addressed and what kind of information are required from them. The importance to improve data reporting from the selected target sectors can subsequently be prioritised in accordance with their relative influence/impact on P flows.

More SFA studies

Another suggestion for further research is simply more SFA studies on P, i.e. where are the losses taking place? In specific on a city and regional scale, as relatively few of these have been conducted so far (see overviews by (Chowdhury et al., 2014; Cordell et al., 2012)).

As we have seen, comparison with other SFA studies on a city scale, show that there is a very diverse nature among the currently conducted SFA studies. This has to do with the difference in system boundaries, chosen processes and context that are defined by the specific local objective of the study (Cordell et al., 2012). Cordell et al. (2012) stress that the specific contexts of cities also make up scaling the results to different geographical scales (regional, national) cumbersome, as one city is not necessarily comparable to another. This stipulates the overall need for greater insight into cities. Such is not only a matter of conducting more SFA studies, but there is also a need for clear categorisation of cities and/or neighbourhoods in urban areas. In doing so, it proved that not only size is a variable of interest, but also population type, buildings types, national background (it is a developing country of developed country?) etc. These are all conditions that affect the outcome of an SFA and clearer typologies of case studies are expected to allow for better comparison. Potentially a framework for categorising cities and neighbourhoods might be developed that could be used for future SFA studies on P. It is also suggested that future SFA studies on an urban scale take notice of P found in MSW flows and specifically P flows related to pets, as this study showed these flows are of importance on the urban level.

Beyond the urban scale, Chowdhury et al. (2014) argue that more knowledge of P flows is required on various geographical scales, in order to realise enhanced P management and to have a more holistic view on the implications of certain actions. They argue that it is especially the regional scale that has not been given proper attention. It can serve as a missing link between the national and the urban studies on P flows. The example is provided of waste recovered on an urban level, applied on a regional level (agricultural land), which on a national scale would reduce fertiliser input. Especially since a regional scale can also encapsulate agricultural and industrial flows, which are often outside city borders. The inclusion of these sectors would allow the potential for P exchange between cities and region to become more visible. This thesis was limited to Wageningen only, yet it is part of an interesting agricultural region, where it might be valuable to explore the potential of direct exchange of P flows. From this thesis it also appeared that taking a regional perspective with regard to P flows, is especially valuable when dealing with smaller cities. Collaboration within the region could facilitate P reuse and recycling where the single urban scale proves to have too little impact.

Longitudinal studies of same case

As a single SFA merely presents a snapshot of P flows, it is recommended more longitudinal studies are carried out. This would provide a better basis for making policy changes and would also allow to understand the effect of certain historical (policy) developments on the destination of P.

Holistic perspective

Finally, complimentary research such as this combined thesis-project is crucial in a sense, as the answer to ensuring improved P management is never confined to one single field of research. Constructing an SFA on P flows through a city is only a part of the information. Yes, it indeed shows the hotspots and the associated focal areas. Yet, being able to take action has also shown to be very much depending on market forces, governance, land rights and many other variables of concern. Chowdhury et al. (2014) therefore suggest to take for example spatial heterogeneity into account: to which sector does the land belong, c.q. which party is in the position to make decisions? Such complimentary research gives a more profound insight into the feasibility of potential plans for redirecting P flows. It also provides a clear notion of potential parties for collaboration. Also incorporating the knowledge from climate change studies and land use changes, as all of this affects the formulation of an effective, long term policy on P. Here, the vulnerability framework recently designed by Cordell and Neset (2014) could prove beneficial and ought to be applied in studies. Through its use, it can also be further refined. This framework has an emphasis on the national scale, yet the authors admit that often vulnerability is context specific and therefore more local (urban) or regional analyses of P vulnerability are vital.

Following this notion of a more holistic perspective, it is also expected that a chain perspective on P is a very valuable addition. As there is a global trade of products, containing P, more knowledge and insight is required into the chain. Although an overview of losses at each stage is already presented by Cordell et al. (2010)[142] (see section 4.3.5), further chain research on P could also aid in understanding the effects of actions at a single stage of the chain on the entire chain. Especially from an urban perspective, which are responsible for much of the P demand, investigating the effects of policies at the urban level throughout the chain would be a valuable addition. It would allow more insight into the contribution of urban areas to closing the loop on P. Furthermore, by taking a chain perspective one would enhance insight into the requirements for meeting supply and demand. The focus of this thesis has been on ensuring P from waste streams can be reused or recycled. For the loop to actually be closed on P, the need for matching this supply and demand is crucial.

[142] Although losses have been researched, Cordell et al. (2012) also argue that the chain is often simplified, yet in reality is extensive and encompasses many sectors and subsectors. Therefore, a more accurate assessment of P throughout the chain would still be an important contribution to existing research.

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Appendices

Appendix I: Data collection per subsector of P output

Wastewater: households

The calculated P flows in WW originating from households include human excreta, fish (aquarium) excreta and food waste going down the drain.

Quantity: The quantity of P in human excreta was based on several studies concerning the Dutch daily dietary P intake in mg/day: from age 2 to 6 (RIVM, 2008), from age 7 to 69 (RIVM, 2011b) and from age 70 and older (RIVM, 2013a). Dietary intake of children from 0 to 2 is not known, but for simplification presumed to be the same as the age group of children from 2 to 4. Kalmykova et al. (2012) make the assumption that 100 % of all dietary P intake is excreted. In the afore-mentioned studies by RIVM (2013a, 2011a, 2008), a distinction is made (in percentage) between consumption at home and not at home. This was used to calculate how much of the dietary P intake is excreted at households.

The quantity of P in aquarium fish excreta is also based on the same principal of estimated dietary P intake derived from calculations made by Kirsimaa and Van Dijk (2013).

The quantity of P in food waste down the drain within households is estimated on the basis of a study conducted by Van Westerhoven and Steenhuisen (2010).[143] In this study it is calculated how much food waste, as well as its composition, is lost down the drain/per inhabitant/year in the Netherlands and is therefore considered representative. This knowledge is subsequently multiplied by the number of inhabitants in Wageningen in the base year of 2012. The P content for every product category in mg/100g was derived from the NEVO table by RIVM (2011b). Where RIVM (2011b) was not sufficient, other studies have been consulted (in the case of coffee and tea residues, for example).

Wastewater: non-households

The P flows in WW originating from non-households include human excreta and food waste going down the drain.

Quantity: The quantity of P in WW from non-household sectors originating from human excreta is known through calculations based on studies mentioned above (RIVM, 2013a, 2011b, 2008). The percentage of daily dietary P intake that is *not* consumed at home is presumed to be excreted outside the house. In addition to excreta, it is expected that non-households also dispose of food waste down the drain. Due to a lack of data it is not possible to calculate this exact P flow originating from the non-household sector.

[143] Recently, a new version of this study focused on household waste was published in October 2013 (van Westerhoven, 2013). At that time, for this thesis, already data from the previous study conducted in 2010 was used. In the most recent report, it is mentioned that little to no change has occurred in comparison to the findings of the 2010 study (van Westerhoven, 2013). This was also confirmed by the author through personal communication (Marcel van Westerhoven, personal communication, January 16, 2014). Therefore, the study of 2010 (van Westerhoven and Steenhuisen, 2010) is still found sufficiently suitable and representative for calculations of household food waste.

For an accurate estimation of P in WW originating from food waste, the data on the total P influent of the WW treatment plant in Renkum is used (Waterschap Vallei en Veluwe, 2012). The total P influent at the WWTP originates partly from Renkum and partly from Wageningen. The amount of P 'assigned' to Renkum and Wageningen respectively, is based on the relative amount of WW (in L) coming from Renkum and Wageningen (van der Molen, 2012) multiplied by the amount of P present in WW (in mg/L) according to the WWTP (Waterschap Vallei en Veluwe, 2012). The amount of P found in WW is however not solely due to food and excreta. According to Willem Schipper (personal communication, November 27, 2013), former senior chemist at Thermphos B.V., other significant sources of P are found to be sanitary paper[144] and dish washer tablets[145]. These non-food related sources of P are calculated for Wageningen. The total P coming from these sources, together with the calculated P originating from households, is deducted from the total P influent of Wageningen. This allows to make a fairly accurate estimation of the amount of food-related P found in WW from non-households.

Municipal solid waste: households

In municipal solid waste (MSW) from households, two food related waste streams are present: food waste related to human consumption, together with food waste related to pet consumption and pet excreta.

Quantity: The calculations for the quantity of food waste related to human consumption are based on the study conducted by Van Westerhoven and Steenhuisen (2010). Van Westerhoven and Steenhuisen (2010) conducted an extensive research (that also included sorting analyses) on household food waste in the Netherlands. Therefore it is considered the most accurate source for making estimations on the amount of P originating from households.

The amount of pet food wasted is based on Kalmykova et al. (2012), who estimate that 10 % of total pet food imported in the urban area is wasted. The amount of P originating from pet excreta is based on the dietary intake per pet multiplied by the number of estimated pets (differentiated per type) in Wageningen. The total dietary intake per pet 'type' is based on calculations made by Kirsimaa and Van Dijk (2013) that estimated the 'feed P consumption per pet in kg/pet/year' and on Baker et al. (2007). The number of pets per type present in Wageningen is based on a study by Borst et al. (2011). This study has researched the number of pets per type present in the *whole* of the Netherlands. It is assumed that all types of pets mentioned in this study are present in Wageningen, ranging from cats and dogs to fish and carrier pigeons. Wageningen is a small municipality with a lot of green space for walking dogs, and households are expected to have gardens that allow for ponds. Even an association for keeping carrier pigeons is present (Centrum voor Jeugd en Gezin Wageningen, 2013). The number of pets (per type) in Wageningen is based on taking the calculated

[144] With regard to sanitary paper, a study by FAO (2013a) was used on the amount of 'household and sanitary paper' produced in the Netherlands (adding import and subtracting export). This was then multiplied with the fraction of P present in paper based on Kalmykova et al. (2012). Thereafter, the total amount for the Netherlands was recalculated (downscaled) for the population of Wageningen (by calculating the fraction of population in Wageningen of total population in the Netherlands) (CBS, 2013c; Gemeente Wageningen, 2012d). As the category used by FAO (2013a) also contains household paper, the assumption is made that of the total, only 90 % concerns sanitary paper.

[145] For estimating the amount of P coming from dishwasher tablets, Deltares and TNO (2013) was used as well as the expertise of Bert Smit, researcher at WUR, and Willem Schipper (Kimo van Dijk, personal communication, November 27, 2013). For households, the study by Deltares and TNO (2013) allowed for an estimation of the number of households that use a dishwasher. For non-households it is assumed that half of all businesses also have a dishwasher.

fraction of households present in Wageningen (CBS, 2012) compared with the number of households in the Netherlands (CBS, 2013b). Subsequently, this fraction is applied to the total number of pets per type present in the whole of the Netherlands (Borst et al., 2011) to estimate the number of pets per type present in Wageningen. The actual number may be different, as there are a lot of students in Wageningen that might not house pets. However, a lack of data on the specific local context resulted in using the afore-mentioned method of calculation.

Composition and P content: The composition of food waste related to human consumption is based on the same study by Van Westerhoven and Steenhuisen (2010). The phosphorus (P) content of a defined product category such as 'meat' is further operationalized, because various types of meat have different P content. The P content for every product category in mg/100g was derived from the NEVO table by RIVM (2011b). Where RIVM (2011b) was not sufficient, other studies have been consulted (in the case of coffee and tea residues for example).[146]

For pet food, there was no need to consider the composition of the food to calculate the P flow. The amount of P in pet food is directly derived from calculations made by Kirsimaa and Van Dijk (2013) and Baker et al. (2007).

Destination: The destination of food waste related to human consumption is also derived from the study by Van Westerhoven and Steenhuisen (2010). This source was found more accurate than data from the municipality of Wageningen (Gemeente Wageningen, 2012a), since Van Westerhoven and Steenhuisen (2010) focused on food waste only[147]. In addition to this source, a report on the municipal waste strategy was used to more accurately assess the disposal methods of food waste in Wageningen (Gemeente Wageningen, 2012a). According to this source, some households have a home composting tank. What otherwise would have been collected as separated 'organic waste' (also known as GFT in the Netherlands[148]) by the municipal waste collector is in the case of home composting assumed to be disposed of in the composting tank.

The destination of pet excreta is based on literature, public information on disposal of pet excreta from the municipality of Wageningen (Gemeente Wageningen, 2012c) and certain assumptions about the context of Wageningen (lot of surrounding nature that allows cats and dogs to walk freely).

Municipal solid waste: hospitality sector

In this study, the hospitality sector comprises of Restaurants, Quick Service Restaurants (QSRs), Pubs (cafés), and Hotels.

Quantity: To make an estimation of the quantity of food waste, a WRAP study (WRAP, 2013a) is used. The report makes estimates of total mixed waste/site/yr and total recycled waste/site/yr in the hospitality sector. These estimates are divided per subsector (Restaurant, QSR, Pub, Hotel) and by size of the 'site' (based on the number of employees). The hotels in Wageningen were contacted to assess their actual size (based on number of employees) for calculating an estimated amount of

[146] Recently, an updated NEVO table was published by RIVM (RIVM, 2013b). At that time, for this thesis, already data from the previous table from 2011 was used. RIVM (2013c) did not announce any changes in the P values of food and therefore, it is assumed that the use of the 2011 publication (RIVM, 2011a) has little to no effect on the calculations of P.
[147] The municipality of Wageningen (Gemeente Wageningen, 2012a) does have numbers on the total organic waste stream (also known as GFT in the Netherlands) and mixed waste collected from households, as well as the amount of organic waste found in mixed waste. However, 'organic waste' from households is not only food waste, but also contains garden waste.
[148] GFT in Dutch stands for vegetables (Groente), fruit (Fruit) and garden waste (Tuinafval) combined.

mixed and recycled waste produced in t/yr. Restaurants, Pubs and QSR's were considered to many to contact individually to assess their size. Therefore, it is assumed that half of all Restaurants, Pubs and QSR's have an employee size band from 5 to 9 and the other half an employee size band from 10 to 19.

Out of the total mixed and recycled waste it is important to know the fraction of food waste for all the four subsectors (Restaurants, QSRs, Pubs and Hotels). The same report has data on the amount (in t/yr) of food waste that is disposed of in the mixed waste and the amount of food waste that is disposed of as recycled waste per subsector (WRAP, 2013a). Liquids and their disposal method (recycled or mixed waste) are also mentioned. As liquids might contain P (milk, beverages etc.) it is taken up in the total amount of food waste. There is a high fraction of total liquids that is recycled and this is assumed to be cooking oil for the following reasons: First, according to various studies cooking oil is commonly recycled in the hospitality industry (CREM, 2010; WRAP, 2011). Secondly, it is mentioned in earlier WRAP study that the largest fraction of total liquids is cooking oil (WRAP, 2011). This explains that the largest fraction of total liquids is recycled. Since cooking oil does not contain any P (RIVM, 2011a), the total amount of recycled liquids (which are all assumed to be cooking oil), are thus not considered in this study. The liquids found in the mixed waste however, are assumed to be beverages that are still packaged and therefore taken up in the calculation of total food waste.

Composition and P content: Before the total P flow can be calculated, it is necessary to assess the composition of food waste per disposal method (mixed or recycled) *and* per subsector. The food waste composition presented in a WRAP (2013b) study was found insufficient: Figure 2.5 only presents an overview of the *entire* Hospitality and Food Service sector (including staff catering, education, hospital etc.). This is too general, as the composition of food waste of each subsector is expected to be very different.[149] Figure 2.6 however, does provide a more detailed composition per subsector, but exact division is unclear in this figure (the percentage can only be vaguely estimated and some categories are not specific, such as unavoidable other food waste) (WRAP, 2013a). Therefore, the composition of food waste for *restaurants* is based on a study by Luitjes (2007). This study researched food waste at 50 restaurants in the Netherlands and is therefore considered to be sufficiently representative. This study mentions the amount (in percentage) of certain product categories such as 'Meat' and 'Fish' present in the total amount of food waste. Here the category 'other' still needed to be further operationalised and it is assumed that this is a mixture of various product categories that are expected to be used in restaurants (such as dairy).

Furthermore, Luitjes (2007) states that a maximum 35 % of food volume bought, becomes food waste. It was found that 10 % of this 35 % is due to food losses in the kitchen, where peels are mentioned as an example. Therefore, this 10 % of food loss is considered 'unavoidable'. The fraction of 'unavoidable' food waste out of total food waste is thus calculated as follows: 10/35. Taken such 'unavoidable' food losses into account is important, as this determines the calculation of the amount of P in food waste from restaurants (unavoidable food waste such as peels, bones and egg shells

[149] For example, QSRs are expected to have little to no preparatory waste compared to restaurants. Hotels serve breakfast, lunch and dinner which is also different from restaurants. This impacts the composition of food waste and thus the amount of P.

contain a different amount of P than meat or vegetables). Thus, for an accurate calculation of the P flow originating from restaurants, the following is assumed:

- Unavoidable food losses can only occur within categories of Meat and Fish (bones), Fruit and Vegetables (peels, pits) and Other (egg shells and coffee etc.)
- It is assumed 1/2 of total unavoidable food waste is fruit and vegetables. The remaining 1/2 is split evenly over the categories meat, fish and other

For calculating the P flow originating from other subsectors, the categories used in the WRAP report (2013b): 'food waste packaged avoidable', 'food waste loose avoidable', 'food waste unavoidable' and 'liquids' are operationalised. In doing so, I've made use of priority waste categories that are also defined per subsector in figure 2.7 (WRAP, 2013a). These priority categories are weighed twice in calculation of the average P content.

The P content for every product category in mg/100g was derived from the NEVO table by RIVM (2011b). Where RIVM (2011b) was not sufficient, other studies have been consulted (in the case of coffee and tea residues for example.)

Destination: As explained in 'Quantity of food waste' the WRAP report (2013b) defined the amount of food waste recycled and amount of food waste found in mixed waste per subsector. Since the hospitality sector mainly deals with cooked and liquid food, it is assumed the recycled food waste stream is treated as 'swill' and sent to anaerobic digestion (CREM, 2010; WRAP, 2013a).

Municipal solid waste: businesses/offices (BO)

Quantity: Due to time constraints it was not possible to investigate the size of each company in Wageningen and whether it has company catering. To assess the quantity of food waste, the assumption was made that one third of all companies in Wageningen have some form of company catering. Wageningen is a small town and it is expected that many of the companies present, have very little employees or are freelancers and therefore have no actual company catering. The total number of companies in Wageningen in 2012 is derived from the municipality of Wageningen (2013). In the study by Van Westerhoven and Steenhuisen (2010) several companies of various sizes are considered. The amount of food waste is different for each type of company and is expressed in kg/visitor/yr. Therefore, the next step is to investigate the size of each company and (if possible) the type of company, that is assumed to have company catering.

Statistisch Zakboek Gelderland (Provincie Gelderland, 2013) was used that documents the 20 largest businesses in Wageningen. A big part of this are companies that are part of WUR. As WUR is calculated separately, these companies are not considered. The food waste of the other companies (with an employee range of 100-799) are calculated based on how their size and profile matched with the example companies that took part in the research by Van Westerhoven and Steenhuisen (2010). It is assumed that half of the employees of these companies are customers of the company catering. The other half is expected to bring lunch to the office. For the remaining companies in Wageningen, calculations are based on an average of 20 visitors/day (Company A), as it is expected that overall, companies in Wageningen are fairly small.

For further calculation of the total amount of food waste from company catering, the study by Van Westerhoven and Steenhuisen (2010) becomes somewhat unclear. Figure 3.3, shows the amount of food waste in kg/visitor/yr. It also mentions that for the number of visitors the average of a year is taken. This seems to suggest that the total amount of food waste produced, can be calculated by multiplying kg/visitor/yr with the total number of visitors in a year. On a daily average for company A, the number of visitors is 20. One would have to multiply this by the number of days the catering is expected to receive visitors to know the total number of visitors in a year. Following this reasoning however, the total amount of food waste and calculated P content then becomes extremely high. After contacting Marcel van Westerhoven (personal communication, January 16, 2014), it became clear that the calculation of their study (2010) is actually based on each 'individual' visitor that the company catering receives on a daily basis, over one year. This leads to a different calculation. Taking the example of company A with 20 individual visitors: Within a company it is the same individuals making use of the company catering throughout a year. Each individual visitor over the course of a year, produces 21 kg of food waste that ends up in mixed waste. This number should thus be multiplied by 20 (the average number of individual visitors that make use of company catering) to calculate the total amount of food waste in a year from one company.

The food waste of employees bringing their lunch and disposing of the residues at the workplace is taken into account: 15 % of the total food waste originating from company catering is added to the total food waste flow.

Composition and P content: For the composition of food waste the 'recalculated' composition of company E (van Westerhoven and Steenhuisen, 2010) is taken, which is also used for WUR. Although most companies in Wageningen are more likely to be similar to company A (van Westerhoven and Steenhuisen, 2010) than to WUR, it is mentioned in the same study that the composition of food waste from company A is not very representative. During the research at that specific time, a lot of dairy and soup was disposed of, which distorts the image. This, in addition to time constraints, led to the use of the composition of food waste estimated for the WUR, for all company catering.

The P content for every product category in mg/100g was derived from the NEVO table by RIVM (2011). When this source was not sufficient, other studies have been consulted (in the case of coffee and tea residues for example)

Destination: According to the study by Van Westerhoven and Steenhuisen (2010), all food waste is disposed of either through the sink, or in the mixed waste. However, from the municipal waste collection company in Wageningen, ACV (Anja Spee, personal communication, November 15, 2013), it is understood that from a fraction of businesses that ACV has contracts with, there is separate collection of swill (commercial food waste and residues) and organic waste stream (GFT). The calculated fraction of businesses known to ACV that separate swill and organic waste is applied to all business with company catering.

Municipal solid waste: WUR

Quantity: The report by Van Gansewinkel for Wageningen UR over the year 2012 is used for numbers on amount of mixed waste and swill waste (Wageningen UR, 2013b). Due to the system boundaries, only the WUR locations based in Wageningen are considered. For estimating the amount of food waste present in the mixed waste, the expertise of Joost Manders, Manager Services at EcoSmart, was used. EcoSmart monitors and ensures optimal separation of waste flows within companies. Manders estimated, based on prior sorting analyses conducted at companies, that approximately 12

% of mixed waste is food waste (if separation is *not* taking place) (Joost Manders, personal communication, November 13, 2013).[150] With the exception of Forum building that partly separates food waste, this percentage of 12 % was applied to all mixed waste collected at WUR in Wageningen to calculate total food waste in t/yr. In the Forum building, the calculations of the amount of food waste separated and non-separated, are based on the report of EcoSmart (2012).

Composition and P content: With the exception of Forum, the composition of food waste is for a part (assumed 1/3) expected to be similar to the composition of household food waste, as people bring their lunch to WUR and dispose of the remains. The largest fraction however (2/3), is assumed to be originating from company catering (Monique Groen, personal communication, October 25, 2013). The composition of the largest fraction is based on company E[151] found in the report by Van Westerhoven and Steenhuisen (2010). An important note however, is that in this report the composition of food entails all disposal paths (mixed waste ánd down the drain). Here, only the composition of food waste ending up in the mixed waste is relevant. Therefore, the various product categories mentioned, and their relative fraction of total food waste, are reconsidered and recalculated. For Forum , the composition of mixed waste is assumed to be similar to household food waste, as it is expected that all waste originating from the company catering in Forum is collected separately and ends up as swill. Hence, the composition of swill separately collected at Forum is fully based on the recalculated composition of food waste at company E.

The P content for every product category in mg/100g was derived from the NEVO table by RIVM (2011b). Where RIVM (2011b) was not sufficient, other studies have been consulted (in the case of coffee and tea residues for example).

Destination: The destination of food waste is based on the report by Van Gansewinkel for Wageningen UR over the year 2012 (Wageningen UR, 2013b).

Municipal solid waste: supermarkets

Quantity : There are very few numbers on the quantification of food waste originating from supermarkets (Hilke Bos-Brouwers, personal communication, October 11, 2013). Therefore, the quantity of food waste is based on a Norwegian study from 2007 (Stenmarck et al., 2011) that researched the amount of food waste coming from the largest supermarket chain in Norway: NorgesGruppen (Stenmarck et al., 2011). The identified product categories with the highest amount of waste in this study correspond with another research by Tesco (2013). Therefore, the Norwegian study is considered fairly accurate for supermarkets. Moreover, it is assumed supermarkets in Norway are fairly similar to supermarkets in the Netherlands.

The amount of food waste (in t/yr) from the Norwegian study is a total amount comprised of all retail shops belonging to NorgesGruppen (Stenmarck et al., 2011). These numbers were recalculated to amount of food waste in t/supermarket/yr, by using data on the number of supermarkets NorgesGruppen had in 2007 from the annual report of NorgesGruppen (2007). Subsequently, this

[150] Joost Manders and EcoSmart actually coin the term GFT (organic waste) instead of food waste. However, the assumption is made that organic waste equals food waste, as garden waste at WUR is collected separately (Monique Groen, personal communication, October 25, 2013).
[151] Company E is catering at a university

was multiplied by the number of supermarkets present in Wageningen (Sandra Tiebosch, personal communication, March 13, 2014).

Composition and P content: The P content for every product category in mg/100g was derived from the NEVO table by RIVM (2011b). Where RIVM (2011b) was not sufficient, other studies have been consulted (in the case of coffee and tea residues for example)

Destination: The destination of food waste is somewhat more difficult to assess. Stenmarck et al. (2011) found that the actual management of food waste from the Norwegian study was unknown, but disposal methods are known to be either donation, fermentation (anaerobic digestion), animal feed or mixed waste. Animal feed was not taken into consideration, as it is mentioned by WRAP (2013a) that food waste used as an ingredient in animal feed all originates from manufacturing sector and not from 'supermarkets'. This leaves donation, anaerobic digestion and mixed waste as disposal methods. The calculated amount of food waste per disposal method is based on assumptions derived from reports on food waste in the retail sector.

Appendix II: Overview of flows and quantities baseline, Wageningen, the Netherlands

Flow	Flow name	Flow type[152]	Source	Destination	Category municipal solid waste (MSW) or wastewater (WW	Quantity in t P/yr
F1	(Partial) domestic food supply Renkum	Import	-	Municipality of Renkum	MSW / WW	17.3
F2	Total domestic food supply Wageningen	Import	-	Non-households (Non-HH) (subsystem: Food distribution system)	MSW / WW	38.8
F3	Pet food supply	Import	-	Non-HH (subsystem: Food distribution Non-HH)	MSW	12.4
F4	Food commodities	Inner flow	Non-households (Non-HH) (subsystem: Supermarkets)	Households (HH) (subsystem: Human consumption)	MSW	20.6
F5	Food donation	Inner flow	Non-HH (subsystem: Supermarkets)	HH (subsystem: Human consumption)	MSW	0
F6	Pet food	Inner flow	Non-HH (subsystem: Supermarkets)	HH (subsystem: Pet consumption)	MSW	12.4
F7	Wastewater Renkum	Inner flow	Municipality of Renkum	WWTP (wastewater treatment plant) city of Renkum	WW	17.3
F8	Wastewater Non-households (Non-HH)	Inner flow	Non-HH (subsystem: Food distribution Non-HH)	Wastewater collection system	WW	7.6
F9	Mixed waste Non-HH	Inner flow	Non-HH (subsystem: Mixed waste collection system)	Solid waste collection system	MSW	10.1

[152] There are certain flows outside the administrative borders of Wageningen (these borders are marked by the dotted system boundary line in the SFA), yet not represented as an export flow in the SFA. These flows are marked as ‘outside flow’.

F10	Swill (commercial food waste and residues) Non-HH	Inner flow	Non-HH (subsystem: Separated food waste collection system)	Solid waste collection system	MSW	0.5
F11	Organic waste Non-HH	Inner flow	Non-HH (subsystem: Separated food waste collection system)	Solid waste collection system	MSW	0
F12	Wastewater Households (HH)	Inner flow			WW	15.2
F13	Mixed waste HH	Inner flow	HH (subsystem: Human consumption)	Solid waste collection system	MSW	5
F14	Pet excreta, mixed waste HH	Inner flow	HH (subsystem: Pet consumption)	Solid waste collection system	MSW	2.6
F15	Pet food wasted, mixed waste HH	Inner flow	HH (subsystem: Pet consumption)	Solid waste collection system	MSW	1.2
F16	Pet excreta, organic waste HH	Inner flow	HH (subsystem: Pet consumption)	Solid waste collection system	MSW	2.4
F17	Organic waste HH	Inner flow	HH (subsystem: Human consumption)	Solid waste collection system	MSW	0.5
F18	Organic waste HH	Inner flow	HH (subsystem: Human consumption)	Home-composting	MSW	0
F19	Cat and dog excreta HH	Inner flow	HH (subsystem: Pet consumption)	Lithosphere	none	6
F20	Compost	Inner flow	Home-composting	HH (subsystem: Pond)	MSW	0
F21	Leachate	Inner flow	Home-composting	Lithosphere	MSW	0
F22	Wastewater, influent	Outside flow	Wastewater collection system	WWTP (wastewater treatment plant) city of Renkum	WW	22.8
F23	Wastewater, effluent	Export flow	WWTP (wastewater treatment plant) city of	Hydrosphere (Aquatic environment)	WW	24.2

			Renkum			
F24	Sludge	Outside flow	WWTP (wastewater treatment plant) city of Renkum	WWTP (wastewater treatment plant) city of Ede	WW	15.9
F25	Sludge	Outside flow	WWTP (wastewater treatment plant) city of Ede	GMB	WW	15.9
F26	Dried sludge (bio granulate) as biofuel for power plant Germany	Export flow	GMB	-	WW	15.9
F27	Mixed waste H and Non-HH	Outside flow	Solid waste collection system	Incineration	MSW	18.9
F28	Ashes	Outside flow	Incineration	Infrastructural use (concrete)	MSW	19.2
F29	Organic waste HH	Outside flow	Solid waste collection system	Anaerobic digestion	MSW	2.9
F30	Swill (commercial food waste and residues) Non-HH	Outside flow	Solid waste collection system	Anaerobic digestion	MSW	0.5
F31	Sludge	Outside flow	Anaerobic digestion	Incineration	MSW	0.3
F32	Fertiliser destined for Germany	Export flow	Anaerobic digestion	-	MSW	0.1
F33	Sludge	Outside flow	Anaerobic digestion	Composting	MSW	2.9
F34	Organic waste Non-HH	Outside flow	Solid waste collection system	Composting	MSW	0
F35	Compost	Outside flow	Composting	Agriculture, Horticulture, Boxcomposting, Potting industry NL	MSW	2.9
F36	Food consumed / disposed through drain Non-HH	Inner flow	Food distribution Non-HH	Wastewater collection system	MSW	7.6
F37	Food commodities ending up in solid waste	Inner flow	Food distribution Non-HH	Hospitality sector	MSW	1
F38	Food commodities ending up in solid waste	Inner flow	Food distribution Non-HH	Businesses / Offices	MSW	0.5

F39	Food commodities ending up in solid waste	Inner flow	Food distribution Non-HH	WUR	MSW	0.1
F40	Total food commodities and pet food	Inner flow	Food distribution Non-HH	Supermarkets	MSW	33
F41	Food commodities ending up in solid waste	Inner flow	Food distribution Non-HH	Other	MSW	8.7
F42	Mixed waste	Inner flow	Hospitality sector	Mixed waste collection system	MSW	0.9
F43	Swill (commercial food waste and residues)	Inner flow	Hospitality sector	Separated food waste collection system	MSW	0.1
F44	Mixed waste	Inner flow	Hospitality sector	Mixed waste collection system	MSW	0.2
F45	Organic waste	Inner flow	Businesses / Offices	Separated food waste collection system	MSW	0
F46	Swill (commercial food waste and residues)	Inner flow	Business/ Offices	Separated food waste collection system	MSW	0.3
F47	Swill (commercial food waste and residues)	Inner flow	WUR	Separated food waste collection system	MSW	0.1
F48	Mixed waste	Inner flow	WUR	Mixed waste collection system	MSW	0.1
F49	Swill (commercial food waste and residues)	Inner flow	Supermarkets	Separated food waste collection system	MSW	0.1
F50	Mixed waste	Inner flow	Supermarkets	Mixed waste collection system	MSW	0.1
F51	Food close to due date	Inner flow	Supermarkets	Food banks/charity	MSW	0
F52	Mixed waste	Inner flow	Other	Mixed waste collection system	MSW	7.8
F53	Human excreta and food waste	Inner flow	Human consumption	Household wastewater collection system (kitchen and sanitation)	WW	15.1
F54	Fish (aquarium) excreta	Inner flow	Pet consumption	Household wastewater collection system (kitchen and sanitation)	WW	0.1
F55	Wastewater	Outside flow	Primary settling tank	Denitrification and aeration	WW	36.1
F56	Primary sludge	Outside flow	Primary settling tank	Primary sludge thickening	WW	4
F57	Wastewater	Outside	Denitrification and aeration	Secondary settling tank	WW	36.1

		flow				
F58	Secondary sludge	Outside flow	Secondary settling tank	Primary sludge thickening	WW	12
F59	Total sludge	Outside flow	Primary sludge thickening	Sludge digestion	WW	16
F60	Total sludge	Outside flow	Sludge digestion	Secondary sludge thickening	WW	16
F61	Total sludge	Outside flow	Secondary sludge thickening	Sludge buffer tank	WW	16

Appendix III: Uncertainty of flows

Table 1. Uncertainty categories

Uncertainty categories	Remarks
1 %	Minimal uncertainty
5 %	Low uncertainty
10 %	Low-medium uncertainty
15 %	Medium uncertainty
20 %	Medium-high uncertainty
25 %	High uncertainty
30 % or above	Very high uncertainty

Table 2. Estimated and calculated uncertainty per flow

Flow	Flow name	Estimated uncertainty in percentage (see table 1)	Remarks on estimated uncertainty	Calculated uncertainty in percentage by STAN
F1	(Partial) domestic food supply Renkum	5	Assumed same fraction of P in wastewater related to food as Wageningen. Data obtained from WWTP very accurate. However, this data concerns total P. This number was recalculated for P related to food only. Low uncertainty as calculations are based on fairly accurate studies and assumptions. In addition, Renkum is expected to be similar to Wageningen. Therefore similar uncertainty as Wastewater Non-HH Wageningen.	5
F2	Total domestic food supply Wageningen	20	The initial domestic P input from food supply is based on the Dutch domestic P supply from food. The latter is estimated at 17.5 Mkg P with a dispersion of 3.3 Mkg (Bert Smit, personal communication, November 27, 2013, publication in preparation). From these numbers the uncertainty calculated amounted to approximately 19 %. This was rounded off towards 20 %.	19
F3	Pet food supply	5	Calculations based on fairly accurate estimations (dietary P intake for pets and number of pets in Wageningen)	5
F4	Food commodities	1	Calculations based on accurate and representative studies and sources (Dutch dietary P intake, Dutch household food waste)	1

F5	Food donation		See F51	-
F6	Pet food		See F3	2
F7	Wastewater Renkum		See F1	5
F8	Wastewater Non-households (Non-HH)		See F36	4
F9	Mixed waste Non-HH		See F42, F44, F48, F50, F52. No separate uncertainty estimated, as F9 is sum of afore-mentioned flows.	73
F10	Swill (commercial food waste and residues) Non-HH		See F43, F46, F47, F49. No separate uncertainty estimated, as F10 is sum of afore-mentioned flows.	13
F11	Organic waste Non-HH		See F45	25
F12	Wastewater Households (HH)		See F53, F54. No separate uncertainty estimated, as F12 is sum of afore-mentioned flows.	1
F13	Mixed waste HH	5	Low uncertainty as calculation is based on representative study.	3
F14	Pet excreta, mixed waste HH	10	Calculations based on accurate estimations (dietary P intake for pets and number of pets in Wageningen). However, the estimation of the amount of pet excreta in mixed waste is very rough.	9
F15	Pet food wasted, mixed waste HH	10	Low-medium uncertainty. Calculation based on assumption made in literature (Kalmykova et al., 2012).	10
F16	Pet excreta, organic waste HH	10	Calculations based on fairly accurate estimations (dietary P intake for pets and number of pets in Wageningen). However, the estimation of the amount of pet excreta in organic waste very rough.	10
F17	Organic waste HH	5	Low uncertainty as calculation is based on representative Dutch study.	5
F18	Organic waste HH	5	Low uncertainty as calculations are based on fairly accurate studies/reports.	5
F19	Cat and dog excreta HH	10	Low-medium uncertainty as assumption of cat and dog excreta disposed of on land is very rough.	6
F20	Compost	1	Calculation based on fairly accurate and representative studies. Although uncertainty is estimated to be higher than 1 %, this minimal uncertainty is given to avoid strong fluctuations in amount of flow that might be unrealistic.	5
F21	Leachate	1	Calculation based on fairly accurate and representative studies. Although uncertainty is estimated to be higher than 1 %, this minimal uncertainty is given to avoid strong fluctuations in amount of flow that might be unrealistic.	5
F22	Wastewater, influent		See F8, F12. No separate uncertainty estimated, as F22 is sum of afore-mentioned flows.	1

F23	Wastewater, effluent	1	Minimal uncertainty as this number is based on efficiency data from WWTP	2
F24	Sludge		See F59	2
F25	Sludge		See F59	2
F26	Dried sludge (bio granulate) as biofuel for power plant Germany		See F59	2
F27	Mixed waste HH and Non-HH		See F9, F13, F14, F15. No separate uncertainty estimated, as F27 is sum of afore-mentioned flows.	39
F28	Ashes		See F27, F31. No separate uncertainty estimated, as F28 is sum of afore-mentioned flows.	38
F29	Organic waste HH		See F16, F17. No separate uncertainty estimated, as F29 is sum of afore-mentioned flows.	8
F30	Swill (commercial food waste and residues) Non-HH		See F10	13
F31	Sludge	25	High uncertainty, because calculation is based on many uncertain variables (number of companies where ReFood, via ACV, collects swill from businesses/offices)	13
F32	Fertiliser destined for Germany	25	High uncertainty, because calculation is based on many uncertain variables (number of companies where ReFood, via ACV, collects swill from businesses/offices)	13
F33	Sludge	5	Low uncertainty as largest fraction originates from households and this calculation is based on representative and accurate study.	8
F34	Organic waste Non-HH		See F11	25
F35	Compost		See F33, F34. No separate uncertainty estimated, as F35 is sum of afore-mentioned flows.	8
F36	Food consumed / disposed through drain Non-HH	5	Data obtained from WWTP very accurate. However, this data concerns total P. This number was recalculated for P related to food only. Low uncertainty as calculations are based on accurate studies. The uncertainty is higher than wastewater from households, as this calculation is dependent on more studies and assumptions.	4
F37	Food commodities ending up in solid waste	30	F37 is sum of F42 and F43. In general, the amount of food commodities ending up in waste in hospitality sector is given a high uncertainty, as calculations are based on many variables and many assumptions had to be made.	8

F38	Food commodities ending up in solid waste	40	F38 is sum of F44, F45 and F46. In general, the amount of food commodities ending up in waste from company catering is given a very high uncertainty, as calculations are based on many variables and many assumptions had to be made.	15
F39	Food commodities ending up in solid waste	1	F39 is sum of F47 and F48. Calculations based on accurate data received from WUR.	1
F40	Total food commodities and pet food	5	F40 is sum of F3, F4, F49, F50, F51. Low uncertainty is given, as the calculated number is mostly determined by food commodities for households and pet food, of which uncertainty is estimated 1 % and 5 % respectively (see F3 and F4).	1
F41	Food commodities ending up in solid waste	95	F41 is the amount of P unaccounted for when deducting total calculated P output from total P input. However, the amount of domestic supply (F2) has a medium-high uncertainty, and thus the amount of F41 can vary distinctively. Based on the calculated uncertainty of F2, it is calculated that the minimal amount of P unaccounted for is approx. 1,4 t P/yr. The calculated average amount of P unaccounted for is approx. 8.7 t P/yr. Thus the total number of F41 can fluctuate by approx. 95 %.	84
F42	Mixed waste	10	Calculations based on representative studies. Total food wasted is very uncertain, but fraction of food waste ending up in mixed waste is assumed to be fairly correct (based on the studies).	10
F43	Swill (commercial food waste and residues)	10	Calculations based on representative studies. Total food wasted is very uncertain, but fraction of food waste ending up as swill is assumed to be fairly correct (based on the studies).	10
F44	Mixed waste	25	High uncertainty, because the fraction of food waste ending up in mixed waste is based on many variables and assumptions.	24
F45	Organic waste	25	High uncertainty, because the fraction of food waste ending up in mixed waste is based on many variables and assumptions.	25
F46	Swill (commercial food waste and residues)	25	High uncertainty, because the fraction of food waste ending up in mixed waste is based on many variables and assumptions.	23
F47	Swill (commercial food waste and residues)	1	Calculations based on accurate data received from WUR.	1
F48	Mixed waste	1	Calculations based on accurate data received from WUR.	1
F49	Swill (commercial food waste and residues)	10	Flow has a higher uncertainty than 10 %, because the fraction of food waste ending up as swill is based on many variables and assumptions. However, low-medium uncertainty to avoid to strong fluctuations in amount of flow	10

			that might be unrealistic.	
F50	Mixed waste	10	Flow has a higher uncertainty than 10 %, because the fraction of food waste ending up as mixed waste is based on many variables and assumptions. However, low-medium uncertainty to avoid to strong fluctuations in amount of flow that might be unrealistic.	10
F51	Food close to due date	1	Flow has a higher uncertainty than 10 %, but number of food donated is not likely to be much higher than estimated. Therefore, minimal uncertainty to reduce any fluctuations in flow that might be unrealistic.	-
F52	Mixed waste	95	See F41. Apart from the very high uncertainty in amount, the destination of this residual flow (mixed waste) is also highly uncertain due to lack of knowledge.	84
F53	Human excreta and food waste	1	Data obtained from WWTP very accurate. However, this data concerns total P. This number was recalculated for P related to food only. Minimal uncertainty as calculations are based on studies that are considered accurate and representative.	1
F54	Fish (aquarium) excreta	5	Calculations based on fairly accurate estimations (dietary P intake for pets and number of pets in Wageningen)	5
F55	Wastewater	1	Minimal uncertainty, as calculation is based on accurate source (data on WWTP) and expert judgement.	2
F56	Primary sludge	1	Minimal uncertainty, as calculation is based on accurate source (data on WWTP) and expert judgement.	2
F57	Wastewater		See F55	2
F58	Secondary sludge	1	Minimal uncertainty, as calculation is based on accurate source (data on WWTP)	2
F59	Total sludge	1	Minimal uncertainty, as calculation is based on accurate source (data on WWTP)	2
F60	Total sludge		See F59	2
F61	Total sludge		See F59	2

Appendix IV: Interviews

Contact name	Organisation	Function	Date interview	Data collection and reporting
Kimo van Dijk	Wageningen University, Environmental Sciences, Sub-department of Soil Quality	PhD candidate	09-10-13	In person. No notes – exploratory interview on P and potential interesting contacts.
Bert Smit	Wageningen University, Plant Research International, Agrosystems Research	Researcher	16-10-13	In person. Minute from notes of interview
Rinus van der Molen	Waterschap Vallei en Veluwe (Water board 'Vallei en Veluwe')	Water Cycle Advisor	16-10-13 and 13-03-14	In person. Minute from notes of interview
Wouter de Buck	Nutrient Platform	Secretary Nutrient Platform	18-10-13	Telephone (Skype). Minute from notes of interview
Martin Wilschut	GMB Bioenergie	Manager GMB Water technology	25-10-13 and 13-03-14	Telephone (Skype). Minute from notes of interview
Jan Weijma	LeAF, Wageningen University	Business developer at LeAF and researcher at Wageningen University	30-10-13	In person. Minute from notes of interview
Monique Groen	WUR, Facility management	Occupational Health and Safety, and Environmental expert	25-10-13	In person. Minute from notes of interview
Wim de Jong	Twence	Senior advisor Strategy and Policy	08-11-13	In person. Minute from notes of interview

Jan-Evert van Veldhoven	Waterschap De Dommel (Water board 'De Dommel')	Senior wastewater engineer	01-11-13	Telephone (Skype). Minute from notes of interview
Harry Post	Gemeente Wageningen (Municipality of Wageningen), Sewerage and Water management	Project manager Wewerage and Water management	30-10-13 and 13-03-14	First interview in person and second interview via telephone (skype). Minute from notes of interview
Marco de Mik	AgruniekRijnvallei	Nutritionist	08-11-13	In person. Minute from notes of interview
Gijs Langeveld	Vereniging Afvalbedrijven (business association of waste processing companies)	Organic waste expert	19-03-14	In person. Minute from notes of interview
Rike van de Wiel	Gemeente Wageningen (Municipality of Wageningen)	Policy advisor environment and sustainability	13-03-14	Telephone (Skype). Minute from notes of interview

Appendix V: Example topic list for interview

- Rol van steden bij nutrientenbeheer
  - Solid waste
    - Bijdrage
    - Wat zou hier verbeterd kunnen worden?
  - Afvalwater
    - Struviet
  - Gemeente invloed
    - Kleine gemeenten / grote gemeenten
  - Drivers cities for action
- Match supply and demand
  - Welk schaalniveau?
- Actoren
  - Samenwerking tussen verschillende actoren lokaal / regionaal niveau
  - Concrete namen
  - Key actors op regionaal niveau
- Nexus: food, water en energy
  - Conflicterende doelen?

Appendix VI: Land owned by the WUR in and around Wageningen, the Netherlands

Approximation of administrative borders of Wageningen are marked red.

Land owned by the WUR is highlighted (Jan Schuijt, personal communication, November 14, 2013)