Optimization of Agricultural Nutrient Supply by Incorporating Recycling Fertilizer to Close Nutrient Cycles at the Isle of Dordrecht

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Wageningen University

Agricultural Economics and Rural Policy Group

Master Thesis

Optimization of Agricultural Nutrient Supply by Incorporating Recycling Fertilizer to Close Nutrient Cycles at the Isle of Dordrecht

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Abstract

Current nutrient management practices in modern high-production agriculture, as well as human waste management, jeopardize nutrient cycles which ensure a subsequent delivery of nutrients for food production and endanger the environment. To (re)establish nutrient recycling from the consumers towards agricultural production is a promising solution to these issues. The Isle of Dordrecht in the Netherlands seems a prospective research area as a farmer's cooperation initiated the reuse of organic raw materials and nutrients from the city and surroundings to supply their fields with nutrients. The farmers are interested in fostering a stronger ideologic and physical connection with the city of Dordrecht as well as the nature conservation areas to sustain their prospective position on the Isle and make their agriculture future-proof. This research aims to evaluate the optimal fertilization scheme including recycling fertilizers (struvite, slurry, hygenized sludge and bokashi) on the Isle of Dordrecht under economic and agronomic constraints (nutrient demand for nitrogen and phosphorus) as well as uncertainty to evaluate their implementation potential. This is carried out by utilizing a multi-objective linear programming model over nine periods each representing a growing season including a Monte Carlo simulation (carried out in GAMS). The weighted multi-objective goal function aims at minimizing mineral fertilizer input as well as discounted fertilization costs. Results indicate that in all scenarios phosphorus shows greater recycling potential than nitrogen. However, with an increasing share of recycling fertilizer, the total amount of applied nutrients (especially P) increases indicating a decrease in nutrient efficiency. In scenario 2 phosphorus could be supplied to 100% from recycling resources while nitrogen yields at 61%. When implementing organic recycling fertilizer, the nutrient soil stock plays a decisive role in releasing nutrients over time and accelerates the usage of recycling fertilizer. Additionally, the importance of animal effluents as a substantial contributor to circular agriculture is emphasized by the results of the model.

Keywords: Nutrient recovery, nutrient cycle, nitrogen, phosphorus, human excreta, sewage, fertilizer, human waste, Netherlands, Isle of Dordrecht, compost, bokashi, circularity, GAMS, circular agriculture, linear programming model.

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List of abbreviations

BW	Blackwater (contains urine and faeces)
CI	Confidence interval
DAP	Diammonium phosphate
DM	Dry matter (measurement of mass when completely dried)
FADN	Farm accountancy network
FAO	Food and Agriculture Organization of the United Nations
FM	Fresh matter (measurement of mass including water content)
GAMS	General Algebraic Modeling System
GFT	Groente-, fruit- en tuinafval container (organic waste container)
LP	Linear programming
MOLP	Multi objective linear programming
N	Nitrogen
P	Phosphorus
P_2O_5	Phosphorus pentoxide (reference value of the fertilizer phosphorus content, conversion factor P to P_2O_5: 2.2914)
PMP	Positive mathematical programming
POP	Persistent organic pollutants
SD	Standard deviation
WGO	Weighted goal programming
WWTP	Wastewater treatment plants

1. Introduction

Over the past half-century, the green revolution was the catalyst for a threefold increase in agricultural production. This was mainly brought forward by the advent of synthetic fertilizer, genetically selected plants, pesticides and other developments laying the cornerstone for the significant population increase worldwide (FAO, 2017b). With increasing population and potentially yield-reducing effects of climate change such as droughts and heavy rain the need to increase or sustain agricultural productivity is still in place. To do so, a sufficient supply of essential nutrients such as nitrogen (N) and phosphorus (P) is needed to keep or increase agricultural production in the future (Pradhan, Fischer, van Velthuizen, Reusser, & Kropp, 2015).

However, the progression and development in the agricultural sector were accompanied by the loss of biodiversity, higher dependence on fossil fuels, pollution of soil, air and water resources and endangering the ecosystem sustainability (FAO, 2017a). The current supply of nutrients in modern agriculture and human waste management jeopardize sustainable nutrient cycles and thus the future of modern agriculture (Trimmer & Guest, 2018). Synthetic nitrogen fertilizer production by the Haber-Bosch process relies on fossil fuels producing greenhouse gas emissions. Phosphorus is like crude oil a mined finite resource which is upon depletion in the future (Cordell, Drangert, & White, 2009). Rapidly urbanization accelerates the nutrient disparity by separating food production and consumption leading to nutrient agglomerations in highly urbanized areas. This causes environmental pollution such as water eutrophication (Tuholske et al., 2021).

One solution to these issues is to recover human-derived nutrients and (re)establish closed nutrient cycles by linking urban areas with nearby agriculture (Trimmer & Guest, 2018). This is done by reusing valuable resources such as organic waste, biomass and blackwater (BW) to produce nutrient-rich fertilizers for agricultural use (Buckwell & Nadeu, 2016; Trimmer & Guest, 2018; Wielemaker, 2019). The lack of sustainable nutrient supply for agriculture is also recognized by European policymakers. The urgency for more circular nutrient management was emphasized as part of the New Green Deal. Based on the circular economy action plan, the European Commission emphasized the importance of nutrient streams to ensure sustainable and regenerative food production. Therefore, the Commission aims towards a higher recovery rate of nutrients by making the market for recovered nutrients more attractive (European Commission, 2020). Also Dutch legislation aims at a more circular agriculture and wants to become a global leader in this regard by 2030 (Ministry of Agriculture, Nature and Food Quality of the Netherlands, 2019). However, there are economic and agronomic obstacles when incorporating recycling fertilizers into existing plant production management systems. To overcome these challenges economic considerations from a farmer's perspective, play a key role (Wielemaker & Weijma, 2020).

This topic gains in significance due to the sharp increase in energy prices which led to production curtailment and price peaks for mineral fertilizer in Europe as repercussions of the Ukraine-Russia conflict. In this context European governments force the ambitions to cut reliance on Russian natural resources with hardly predictable consequences for European farmers (Schnitkey et al., 2022). Furthermore, the recent announcement regarding a stricter Dutch fertilizer policy which will further restrict the application of manure in the Netherlands causes social tensions in this regard.

Local cooperation such as the Heathfarm foundation and a farmer's cooperation on the Isle of Dordrecht also recognizes these pressing issues. The farmers are interested in fostering a stronger ideologic and physical connection with the city of Dordrecht as well as the nature conservation areas to sustain their prospective position on the Isle and make their agriculture future-proof. This is mainly brought forward by the cooperating "Foundation Heathland Farms Netherlands" and participating farmers. The underlying concept of the foundation is to implement the traditional infield-outfield farming system to reconnect the intensively cultivated agricultural areas (infields) with the outfields (city of Dordrecht and Biesbosch nature conservation area) (Woestenburg, 2018, 2019).

Based on this background it is of interest to evaluate the maximum substitution rate of mineral fertilizer by recycling fertilizer in the agricultural production on the Isle of Dordrecht. Further, there are agronomic as well as economic constraints that need to be considered in this interrogation. Mainly the nitrogen and phosphorus demands as the two most relevant nutrients in agricultural production need to be satisfied (Blume et al., 2016). Also, organic fertilization accompanied by uncertainty regarding nutrient content and availability is considered. Therefore, the following research questions are relevant:

- What is the optimal recycling fertilizer implementation scheme without jeopardizing the cost constraint and satisfying nutrient demand on the agricultural production on the Isle of Dordrecht?
- To which extent can this optimal nutrient management scheme be stretched on the agricultural production on the Isle of Dordrecht based on the available resources nearby?

I translate these questions into a constrained fertilization problem by using a multi-objective linear programming model carried out in GAMS (General Algebraic Modeling System). Uncertainty is introduced via a Monte Carlo simulation with 10.000 iterations with randomly drawn values for the used parameters. This research contributes to the pressing questions regarding the future nutrient supply of modern European agriculture from a Dutch regional perspective.

The topic of my thesis was initiated by dealing with the traditional infield-outfield farming system in the academic consultancy training as part of my master's study at Wageningen University. In this context, I visited the research area with a group of other students and had the opportunity to interview three of the farmers on the Isle of Dordrecht

Thesis organisation

The remainder of the thesis is organized as follows: the literature section starts by emphasizing the importance of nitrogen and phosphorus for modern agricultural production. Following, current threats to the agricultural nutrient supply such as high dependence on mineral fertilizer, nutrient losses and immobilization and urbanization are introduced. Additionally, I shed light on multi-objective linear programming and a few research applications relating to my topic. In the material and methods chapter, I emphasize the case study area: The Isle of Dordrecht as well as my modelling approach. Further, I present the data for my study. This is followed by the results, discussion and conclusion.

2. Literature

In this chapter, I will shed light on the scientific knowledge backing up the underlying concept of my study. Starting with a short introduction of the role of nitrogen and phosphorus in the current agricultural production systems as well as the threats to the nutrient cycles. Furthermore, I will introduce the concept of nutrient recycling as well as current approaches and state-of-the-art technologies. In closing this chapter, the chosen modelling approach namely multi-objective linear programming (MOLP) is introduced.

2.1. Agronomic aspects of nitrogen and phosphorus

To produce grains and organic matter, plants require a variety of essential nutrients and components. Carbon and oxygen are taken up from the atmosphere as well as the soil vapour, while hydrogen originates from the bottom water in the soil. Additionally, plants require 16 other not substitutable essential elements from the soil and partly atmosphere (nitrogen fixation by legumes). These nutrients (Table 1) are divided into macro-and micronutrients determined by the amount demanded from the plants. Useful elements have beneficial attributes for the plants and can improve their growth or resilience but are not considered essential (Blume et al., 2016).

Table 1: Macro- and micronutrients and useful elements for plant growth (Blume et al., 2016)

Macronutrients	Nitrogen, Potassium, Calcium, Magnesium, Phosphorus, Sulphur, (Silicon)
Micronutrients	Chlorine, Iron, Manganese, Boron, Zinc, Copper, Nickel
Useful elements	Silicium, Natrium, Aluminium, Cobalt and more

Nitrogen has quantity-wise the highest share of all nutrients in the plants and has the strongest influence on the yields and quality of the products. In plants, it is part of amino acids, proteins, vitamins and chlorophyll. The nitrogen in the soil occurs in mineral form or is bound in organic compounds. However, the amount of nitrogen naturally occurring in parent rocks is extremely small and the subsequent yearly delivery from the soil is thus negligible. Therefore, a seasonal supply of nitrogen in the form of mineral or organic fertilizers is needed to meet the plants' demand. Further, the root system of the plants can only take up particular forms of nitrogen: the ionized form of ammonium (NH4+) and nitrate (NO3-). The easily soluble nitrate is more likely to be taken up by the plant but is also at high risk of being washed out of the soil. In contrast, ammonium is for the most part adsorbed in clay minerals and thus ensured against leaching but also less likely to be taken up by the roots (Blume et al., 2016).

Phosphorus is an essential keystone for all living beings. It is a crucial part of the DNA and RNA, bones and energy system. In plants, it is especially important for energy transport (ADP, ATP), as a cellular component (phospholipid bilayer) and for the synthesizing of organic compounds. Phosphor is up taken as an ionized form of phosphoric acid ($H_2PO_{4-}^{2-}$) and hydrogen phosphate (HPO_4^{2-}). These compounds are of importance for the plant's phosphorus uptake, as only 0.1 % of the total soil-P is in the soil solution and thus plant available. The rest can be categorized into stable and unstable P- compounds which are partly or not available for plant uptake. The natural P-content in the soil depends on the composition of the parent rocks in the soil. The range can vary between sandy soils with less than 100 mg P/kg soil up to 800 mg P/kg of soil for heavy loamy and clay soils. Nevertheless, the long-term agricultural use of soils makes seasonal phosphor supply in maintenance applications necessary (Blume et al., 2016).

For this purpose, mineral (inorganic) or organic fertilizer can be utilized. Thereby not only the amount of nutrients brought onto the field but also their availability is decisive and directly linked to agricultural productivity. The nutrient availability in the soil is dependent on a variety of factors such as parental rock material in the soil, particle size, humus and water content, pH, aeration, root surface area and mycorrhiza development (Jackson, 2020). This interaction of interrelated factors makes the nutrient release from the soil unforeseeably. When deciding between mineral (inorganic) and organic fertilizers a variety of factors influence the decision-making process.

Table 2: Inorganic vs organic fertilizer characteristics (European Commission, 2021)

Characteristics	Inorganic fertilizers	Organic fertilizers
Nutrient source	N from the air; P & K from deposits and mines	Crop residues, animal manure, human waste streams
Nutrient concentration	High	Low
Nutrient availability	Immediately available to crops	Variable. Organic material needs to be decomposed to release nutrients
Quality	Consistent	Variable: concentration of nutrients varies a lot and therefore is dependent on raw material sources and climatic conditions that can impact the uptake of nutrients by plants
Economics	Low logistic cost making transport relatively easy	High logistical cost making its transport on long-distance non-financially viable

The nutrient availability in mineral fertilizer is more certain compared to organic fertilizers. In this context, nutrient availability describes the contents of legally designated available nutrients in fertilizer determined by specified laboratory procedures. For organic fertilizer such as manure, it implies the amount of nutrients becoming available during the first growing season after application. With high amounts of nutrients bound in hardly decomposed organic compounds like in straw this figure is rather low (Fageria & Baligar, 2005). Furthermore, the quality of mineral fertilizer is consistent due to standardized production processes and quality controls, while the quality of organic fertilizer is dependent on a variety of influences such as used ingredients, raw material, storage, handling and climatic conditions. Additionally, the physical characteristics of organic fertilizers make extensive transportation costly while mineral fertilizer is better suited to be transported over long distances (European Commission, 2021).

2.2. Threats to nutrient cycles in food production

The implications of current fertilization management of modern, highly intensive agriculture and human waste management jeopardize the nutrient cycles as well as the environment. In the following chapter, I will introduce the main threats to the nutrient cycles which build the foundation for food production. Agricultural dependence on mineral fertilizer as well as nutrient losses and immobilization under current agricultural use will be touched.

Figure 1 displays the basic scheme of key nutrient flows through food production and consumption systems and identifies the potential nutrient recovery streams as well as some key downfalls in the current management system.

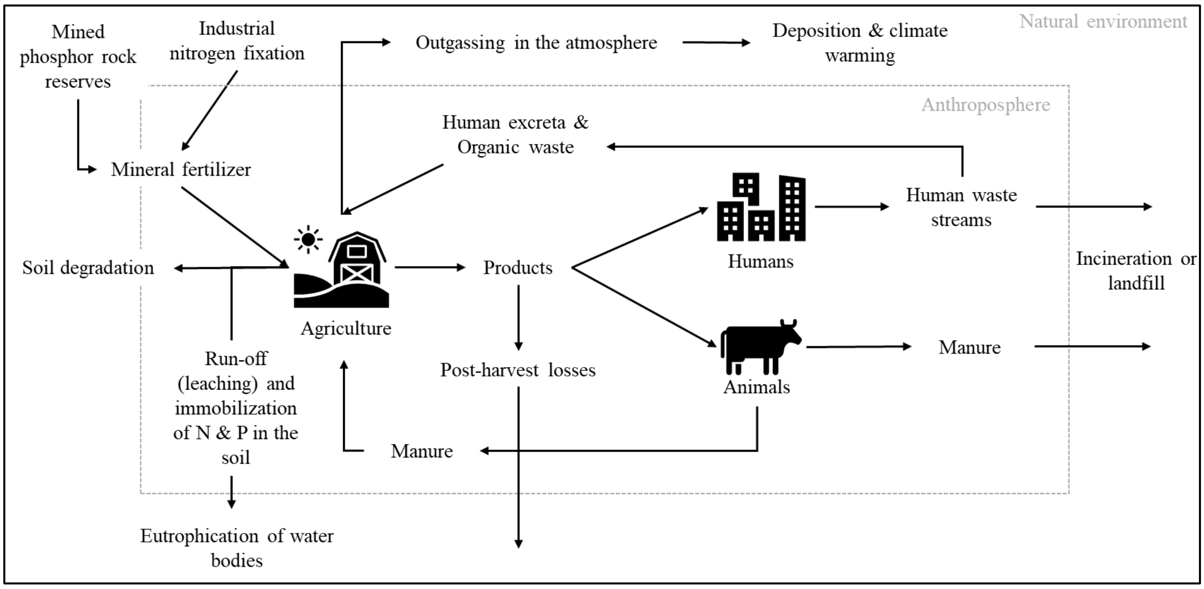

Figure 1: Basic scheme of key nutrient flows through global food production and consumption systems (adapted by Wielemaker, 2019)

Increasing agricultural nutrient demand

Concerning a rapidly rising world, population and rising demand for food agricultural production must increase depending on dietary habits by 60 to 110% by 2050. Furthermore, agricultural production is and will be even more threatened by the effects of climate change such as droughts, flooding and land degradation. Facing these enormous challenges, it is important to increase the world's agricultural production on the already existing arable land (Pradhan et al., 2015). This cannot be achieved without intensive fertilizer use. Therefore, a higher fertilizer demand is forecasted (European Commission 2019). Simultaneously, current fertilization management is depleting the world's soils, which means that the phosphorus input from the atmosphere, weathering and chemical & organic fertilizer versus plant uptake, soil erosion and runoff leads to an average worldwide net phosphorus loss of about 12.8 Tg /yr. Without chemical phosphorus fertilizers, the losses are even higher which underlines the dependency of modern agriculture on these (Alewell et al., 2020).

Agricultural dependence on mineral fertilizer

Before modern and intensive agriculture came into place soil fertility was based on the "natural fertility" of the soil and the additional local organic material such as manure and human excreta – also referred to as night soil (Ferguson, 2014). Starting from the mid-late 19th century, phosphor fertilizers like Guano and phosphate rock were brought in from remote areas (Cordell et al., 2009). Later at the beginning of the 20th century, the energy-intensive Haber Bosch process enabled agricultural production to use artificial nitrogen fertilizer. The Haber-Bosch process uses high temperatures and pressure to fix atmospheric nitrogen and produce liquid ammonia (European Commission, 2019). Together with the "Green Revolution" which introduced new crop varieties and more efficient production technologies the usage of artificial fertilizers was the key driver for the enormous agricultural productivity growth (Cordell et al., 2009; FAO, 2017b)

Nowadays, modern conventional farming is highly dependent on these artificial fertilizers. Currently, the nutrition of 48% of the world's population depends on artificial nitrogen fertilizer (Erisman, Sutton, Galloway, Klimont, & Winiwarter, 2008). With their high amount of fast available nutrients, they offer the possibility of precise fertilization management, which aims at high yields. Tailoring the nutrient supply to the needs of the plants is one of the cornerstones of the massive increase in agricultural production over the last decades. However, the current use of fertilization in modern agriculture has some downfalls with far-reaching consequences for the key nutrient flows in global food production such as nutrient runoff into the environment (Wielemaker, 2019).

Peak phosphorus

Phosphor fertilizers are produced from mined rock and are thus a non-renewable resource. There are only a few suppliers of raw phosphate. The main mining areas are the USA, China and Morocco. The estimated remaining deposits of phosphor will be fully depleted within the next 50 to 90 years. The exploitation of phosphorus is described as a peak curve identifying the maximum point of production followed by the declining production value in the following decades (like peak crude oil). This maximum value of production or mining is forecasted for 2033 (Cordell et al., 2009).

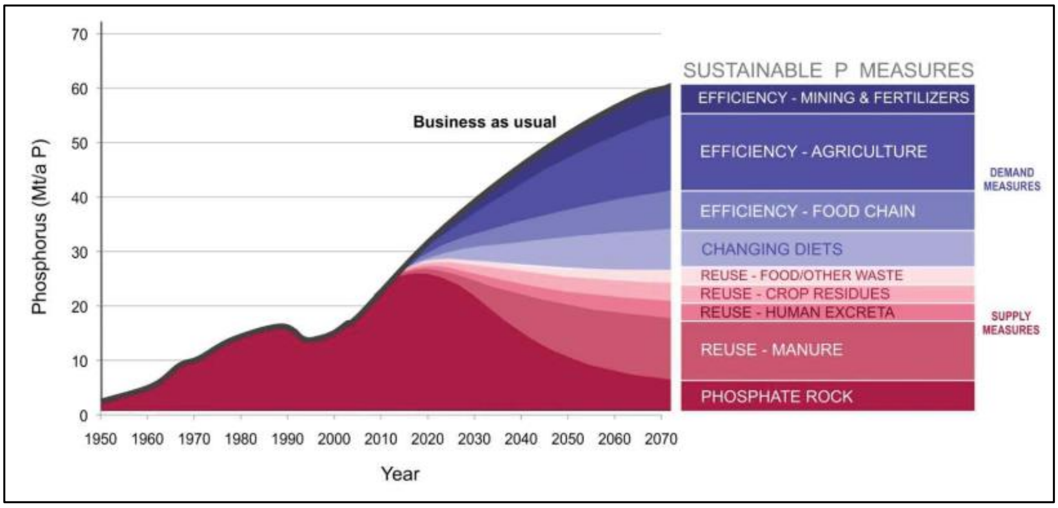

Figure 2: Peak phosphorus curve and sustainable supply measures (Cordell & White, 2013)

Thus, the fertilizer industry faces difficulties as the amount of raw material is decreasing while prices for exploitation and production are increasing. Future access to phosphor as input for agricultural production is highly unpredictable. However, phosphorus is different to crude oil in two points: First, the element phosphorus is not substitutable for food production and cannot be produced artificially. Second phosphorus recovery after usage in agricultural or industrial production is possible and bears the chance to overcome the expected shortages. Figure 2 depicts the peak phosphorus curve as well as sustainable supply measures including the reuse of manure, human excreta, crop residues and food waste. However, the biggest impact on achieving sustainable phosphorus demand according to Cordell and White (2013) is suited in an increase in phosphorus use efficiency in agriculture, food chain and mining.

In contrast, the production of nitrogen fertilizers is not dependent on non-renewable natural resources directly. However, the Haber-Bosch process utilises natural gas (methane) or coal as a resource for energy-intensive nitrogen fixation. Three to five per cent of the global annual natural gas consumption of methane serves as the main energy input for this process. Consequently, the costs for artificial nitrogen fertilizers are highly dependent on the current energy costs (60-80% of the variable input costs) (European Commission, 2019).

Nutrient losses and immobilization

Overfertilization leads to serious environmental harming effects. Nitrate the most common form of nitrogen in the soil is highly at risk of leaching. This leads to the eutrophication of water bodies and groundwater. Further, nitrous oxide emissions (N_2O) evoked by soil compression of heavy machinery and denitrification (reduction of nitrate to nitrogen oxide) contribute to the warming of the atmosphere. Further, the outgassing of ammonia (NH_3) as part of the nitrification process (oxidation of ammonium to nitrate) in the soil leads to acidification of other ecosystems when spaciously conveyed through wind and water (Blume et al., 2016). With more than 70 % of the total nitrogen losses, agriculture is the biggest contributor in Europe. The rest of the losses are evoked by sewage treatment and food waste by the consumers and industry (Buckwell, Nadeu, 2016).

High phosphorus fertilization rates – especially in high livestock areas – lead to a reallocation and enrichment of P in the deeper soil followed by leaching. This process causes eutrophication of groundwater and other waterbodies close to agricultural areas (Blume et al., 2016). Thus, more than 60 % of the annual phosphor losses in Europe are due to agriculture (Buckwell & Nadeu, 2016).

Additionally, nutrient immobilization in agricultural soils is an important factor and process in the nutrient cycle as the nutrients are no longer available for the plants and additional fertilizer is needed to meet the plants' demands. Nitrogen is immobilized due to fixation in soil minerals and binding in soil organic matter. The nitrogen from organic matter is released by the process of mineralization. Mineralization is the microbial conversion of organic nitrogen compounds into plant-available inorganic NO3- and NH4+ ions. Microbes need the nitrogen and carbon that are released from the organic compounds during the mineralization as energy supply. If the amount of nitrogen that is taken up by the microbes during this process is larger than the released nitrogen it is immobilized by the microbes and not plant available. The process of mineralization is depending on many environmental factors and is thus highly unpredictable for the farmers applying organic fertilizers. Nutrient and tillage management can only partly influence this process (Blume et al., 2016; Brust, 2019).

Immobilization plays a bigger role in phosphorus. As mentioned earlier, only a small amount of P is available for plants (less than 0,1 % of total P). The phosphor bound in unstable compounds like soil minerals or unstable organic compounds can be made available by reducing the pH value in the soil solution or the utilization of mycorrhiza (Blume et al., 2016). However, due to the low potential of mobilization of phosphorus in the soil a subsequent high delivery of fast available P by mineral fertilizer is needed. This is most often achieved by a pre-treatment of raw phosphate, which increases the share of available P in the fertilizer.

Urbanization

Today already more than 50 % of the world's population is living in cities. The ongoing urbanization is characterized by the increasing number of people living in urban areas as well as the development of megacities (OECD, 2015). This increasing amount of people living in big urban areas poses a big challenge to the sustainable and environmental management of their waste streams. For instance, increasing amounts of human excreta from urban areas can cause environmental harm when being released into the water bodies through emissions. The municipality's solid waste (and urban organic waste) is expected to increase exponentially in the next decade (Adhikari, Trémier, Martinez, & Barrington, 2010). Additionally. The shift to a major urban population relocates the place of food consumption – the demand side – from the place of food production. The transportation of groceries from different places into the urban areas leads to a high concentration of nutrients there (Wielemaker, 2019). However, this process entails a high potential for nutrient recovery in urban areas.

2.3. Nutrient recovery from urban areas

The conglomeration of nutrients evoked by urbanization, agricultural specialization and globalization render cities and urban areas especially attractive to put effort into the recycling process (Cordell et al., 2009; Wielemaker, 2019). Further, the harmful environmental consequences of the treatment and processing of human waste streams can be circumvented by a higher recovery rate. However, the economic incentive to introduce higher nutrient recovery is low. Mineral fertilizers had low prices in the last decades and make higher efforts to increase nutrient recovery economically unattractive. The main sources of nutrient recovery from human waste streams are sewage from human excreta and food chain waste (Buckwell & Nadeu, 2016).

Human excreta which also called blackwater (BW) contains urine and faeces is an enormous and largely unexploited source of nutrients and has the potential to bring back organic matter to the agricultural soils especially for agricultural enterprises without animals (Buckwell & Nadeu, 2016; Cordell et al., 2009; Wielemaker, 2019). Conventionally the sewage stemming from human excreta is processed into sludge in the so-called “Waste Water Treatment Plants (WWTP)”. Sludge is defined as “a semifluid mass of sediment resulting from the treatment of water, sewage and other wastes” (European Environment Agency, 2022). The nutrients in sewage sludge can be made available by composting, anaerobic digestion and other stabilisation processes (Figure 3).

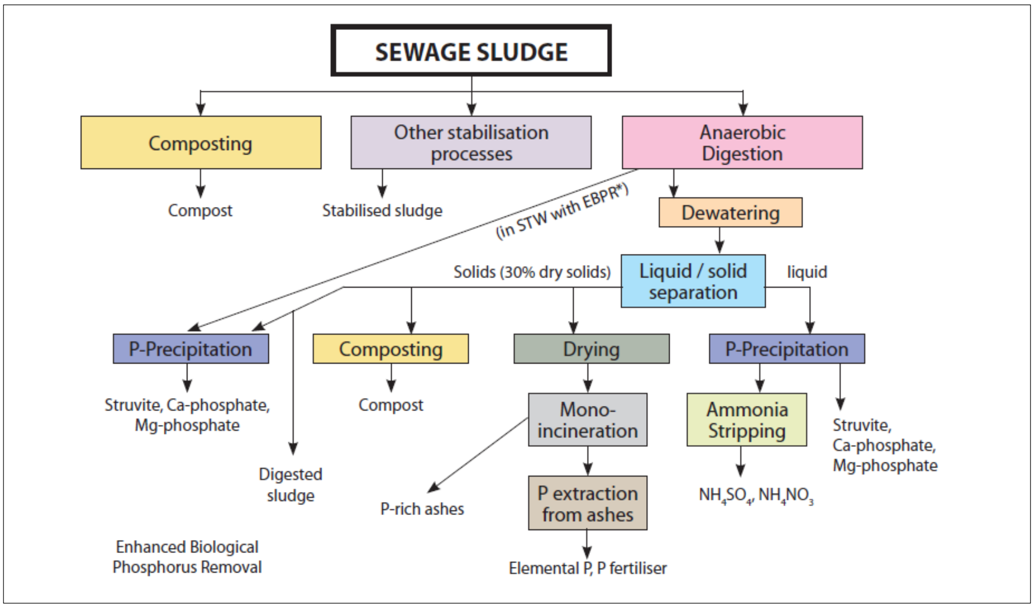

Figure 3: Main roots and products of nutrient recovery from sewage sludge (Buckwell & Nadeu, 2016).

Food chain waste can be further divided into municipal solid waste, biodegradable waste from the food industry and slaughterhouse waste. The nitrogen content of municipal solid waste ranges from 2 to 3%, while phosphorus has a share of around 0,5%. Around 30% of the potentially recovered nutrients in municipal waste on the European level are recovered by making compost. Increasing this share to the maximum could substitute 10% of the current agriculture-applied phosphor fertilizer. Due to the high share of organic matter in municipal compost also a reduction of soil degradation could be achieved with an increased application. The disadvantage of compost as agricultural fertilizer is the majority of the available nitrogen and phosphor is bound in the organic fraction and thus only slow releasing. Due to this unreliability of nutrient release compost is rather considered to be a soil improver instead of a fertilizer (Buckwell & Nadeu, 2016).

Further, ways of processing food chain waste are anaerobic digestion and incineration (see Figure 4). Digestate has the advantage of higher and more homogeneous nutrient content compared to compost and allows for simultaneous energy production. Incineration produces ashes that deliver high phosphorus values. Incineration is also the primary way of processing slaughterhouse waste. The resulting ashes are based on slaughterhouse waste containing for example bones and are high in phosphorus (22 %).

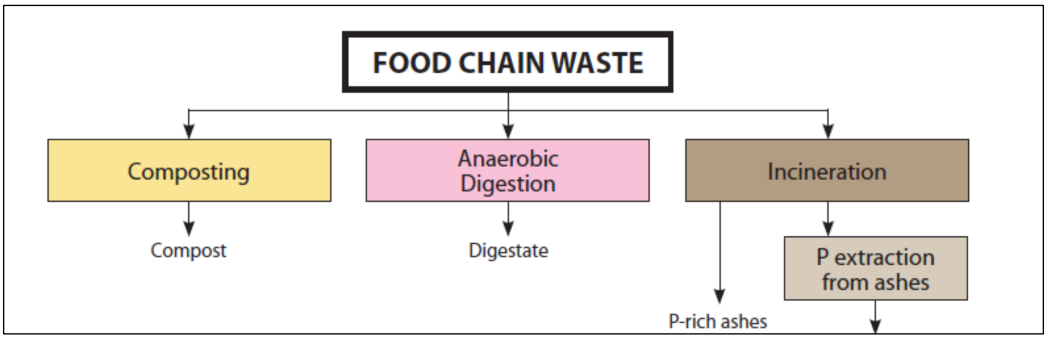

Figure 4: Main roots and products of nutrient recovery from food chain waste (Buckwell & Nadeu, 2016).

The third fraction of food chain waste is biodegradable waste from the food industry. This is comprised of all kinds of waste materials from small bakeries to big sugarbeet factories for example. Thus, the amount and nutrient composition are hard to estimate and require a more specific region (or city-wise) estimation (Buckwell & Nadeu, 2016).

2.4. Recycling fertilizer

In the following paragraphs, I introduce the recycling technologies and fertilizers which are of interest at the Isle of Dordrecht and further used for my model: Bokashi, struvite, hygenized sewage and slurry. I provide some background on the general suitability as fertilizer as well as their current usage in European and Dutch agriculture. In the end, I provide a short chapter emphasizing the topic of contaminants in recycling and mineral fertilizer.

Bokashi

Bokashi, which has its origin in Japan, stands for "good fermented organic matter" and is the product of the anaerobic conversion (lactic acid fermentation) of organic materials. In this process, effective microorganisms (EM) are breaking down the complex structures of the organic raw materials and produce a nutrient-rich product that can be used as an organic fertilizer. Organic raw materials such as food waste, green cuttings or other biomass need to be chopped and piled. Through the addition of EM, the fermentation process is started and takes approximately 21 days. The advantages of bokashi compared to the conventional process of composting are manifold. First, the nutrient losses between raw materials and end products are lower in bokashi compared to compost. Further, the emissions of greenhouse gases during the process are significantly lower. Additionally, the production of bokashi is less labour-intensive as no restacking is needed. Also, the viability of pathogens is suppressed by the anaerobic conditions while the C/N-ratio (carbon to nitrogen ratio determining the degradation rate in the soil) is more beneficial to the soil life (Bosch, Hitman, & Hoekstra, 2017; Olle, 2021).

While Bokashi has high popularity in the Asian and Oceanian regions, it is not yet widespread in Europe. Up to date only a small proportion (5% of the fertilizer market in the volume of nutrients) of organic raw material is processed and marketed as commercial fertilizer in the European Union (European Commission, 2021). Approximately 40 Bokashi project initiatives are currently operating in the Netherlands monitored by the Dutch organization *Circulair Terreinbeheer* (Circular Terreinbeheer, 2022). It is the objective of the farmers' initiative on the Isle of Dordrecht to synthesize one organic fertilizer using the different organic waste streams from the outfields. Instead of buying an already finished fertilizer like compost, the farmers want to carry out the processing by themselves and potentially scale up the production. First and foremost, the idea behind is to use the organic fertilizer on their arable land and prospectively sell it to other farmers in the area. Instead of composting the organic raw materials, the farmers' preferred option is anaerobic fermentation leading to Bokashi.

One of the farmers at the Isle of Dordrecht is experimenting and producing bokashi on his farm already. Samples were taken from the bokashi production on his farm indicating a nutrient content of 3.1 kg N and 1.3 kg P_2O_5 per tonne of fresh matter (FM: fresh matter includes the water content in the raw material, dry matter content + water content = fresh matter). Effectively this leads to a nutrient content of 0.52% N and 0.22% P_2O_5 per dry matter (DM). The organic matter content is 15.8%. (Groen Agro Control, 2021). So far, the bokashi is mainly fed from biomass low in nutrients such as chopped wood and green cuttings. Assuming that the GFT (Groente-, fruit- en tuinafval container) from the City of Dordrecht is made available and treated by anaerobic fermentation the nutrient content in the bokashi will be significantly higher.

Struvite

Struvite ($NH_4MgPO_4 \cdot 6H_2O$) precipitation is an application to recover ammonia and phosphorus from human wastewater (especially urine). The white crystalline mineral can be obtained from source-separated urine or blackwater (urea and faeces) treated in a biogas plant or industrial wastewater such as from potato or sugarbeet manufacturers. To initiate the precipitation process magnesium must be added. Suitable magnesium sources are the bittern, magnesite rock or wood ash (Kabadsli, Tünay, & Udert, 2013).

Figure 5: CrystalGreen® struvite fertilizer (Korzekwa, 2022)

Currently, in Europe 39 operational struvite production sites recycle 0.5 % of the phosphorus available in wastewater and process it into a fertilizer which meets EU legislation requirements. Based on numbers from 2017 this corresponds to 0.06-0.07% of the EU imported phosphorus fertilizer (Muys et al., 2021). Initiated by the Ministry of Economic Affairs and the Ministry of Infrastructure and Environment in 2015 the application of struvite fertilizer was permitted in the Netherlands (Manure and Fertiliser Act, 2014). Currently, between 9000 and 12000 tons of struvite are produced in the Netherlands which accounts for 35 to 43% of the total produced struvite in the EU (Muys et al., 2021). The agronomic performance of struvite ranges between rock phosphate and soluble mineral P fertilizer (like superphosphate). Due to its low solubility in water, it is characterized as slow release fertilizer, meaning that it constantly releases P over the growing season (Weissengruber, Möller, Puschenreiter, & Friedel, 2018). The basis for my model is the commercially available fertilizer CrystalGreen® as provided by Ostara Nutrient Recovery Technologies Inc. containing 5% N and 28% P_2O_5 (Talboys et al., 2015).

Hygenized sludge

Currently, around 40 % of the sludge is brought back to agricultural land in the European Union (EU 27). However, the share varies significantly among the member states from 0% e.g. Belgium and the Netherlands up to 90 % in Portugal. In the Netherlands, the application of sewage sludge is highly restricted and almost fully forbidden (Rizzardini & Goi, 2014). Thus, the potential for improvement and utilization is high in this direction (Buckwell & Nadeu, 2016).

To avoid high loadings of pathogens and viruses in the sewage sludge hygenization is recommended for agricultural reuse. To further prevent the accumulation of contaminants in agricultural soils there are recommendations for the maximum application within a given timeframe. In Germany for instance the maximum application limit is 5 t DM (100m^3 FM) sewage sludge allocated over three years (Wiechmann, Dienemann, Kabbe, Brandt, & Roskosch, 2013). There are several treatment options as well as new sanitation systems like source separation – separation of urine and faeces – and decentralisation which might reduce losses and offer a higher potential for nutrient recovery from wastewater. Innovation and changes to conventional wastewater management seem inevitable in the future as incineration and other conventional wastewater treatments potentially polluting waterbodies are not sustainable (Larsen & Gujer Willi, 2013; van Puijenbroek, Beusen, & Bouwman, 2019).

Animal effluents

Animal manure is a valuable fertilizer rich in macro-and micronutrients as well as organic matter and is considered a recycling fertilizer. It is the main contributor to achieving a closed nutrient cycle within an agricultural enterprise or regional area. It has excellent soil enhancing attributes stimulating soil biology and adding organic matter. However, the overproduction and oversupply of animal effluents in regions with high livestock density lead to the fact that they become useless waste rather than a valuable organic fertilizer (Cremer, L. D. L. L., 1985). This is since application rates on cropland are limited by governmental institutions to avoid the environmental harming effects of nutrient runoff. This leads to a situation where manure is sometimes seen as a waste product with high disposal costs. The Netherlands as a relatively small country with high livestock density has a nutrient surplus. Evoked by large amounts of feedstuff imports and import of mineral fertilizer the nutrient supply outweighs the nutrient demand. The amounts of nitrogen and phosphorus contained in Dutch livestock feed imports exceed the amounts of nutrients imported via mineral fertilizer. Hence it is upon discussion to which extent animal manure can be considered a recycling fertilizer as it amplifies the dependence on foreign resources (Smit, van Middelkoop, van Dijk, & van Reuler, 2015; Wageningen UR Livestock Research, 2014).

Contaminants in recycling fertilizers

One of the potential drawbacks of utilizing and recovering nutrients from human or animal waste streams is their contamination with pollutants (Figure 6). Among these are heavy metals like cadmium, arsenic, mercury or lead, microplastics, pharmaceuticals, persistent organic pollutants (POPs) or pesticides (European Commission, 2021). Most of which is associated with the application of sewage sludge containing pollutants from households, businesses and other sources. Due to its inhomogeneity and differences in components, the concentrations can vary substantially. Also, the effects of these pollutants on soil and groundwater are hard to determine. However, the heavy metal loads are relatively low in sewage sludge allowing for a moderate application. Further, the appearance of pharmaceuticals in sewage sludge as a result of therapeutic use or improperly disposal poses a risk to the environment. WWTP are often not designed or technically equipped to remove pharmaceuticals efficiently so that pharmaceuticals are remaining in the sludge. In this regard, improvements need to be made to ensure a sufficient removal (Wiechmann et al., 2013).

Also, the application of conventionally used fertilizer like manure, slurry or mineral phosphorus fertilizer bears a high risk of contamination. A recent evaluation of the European Commission (2021) emphasized that mineral phosphorus fertilizer is currently the main contributor to cadmium accumulation in the agricultural environment. Animal effluents can also contain high amounts of heavy metals provoked by feed additives. Further, the high animal density in the stables and resulting high infection pressure and use of antibiotics pollute animal effluents for further agricultural use (Bloem et al., 2017). Consequentially a repeated application of contaminated organic nutrient sources such as animal manure or sewage sludge promotes the creation of antibiotic-resistant genes (Zhang et al., 2015).

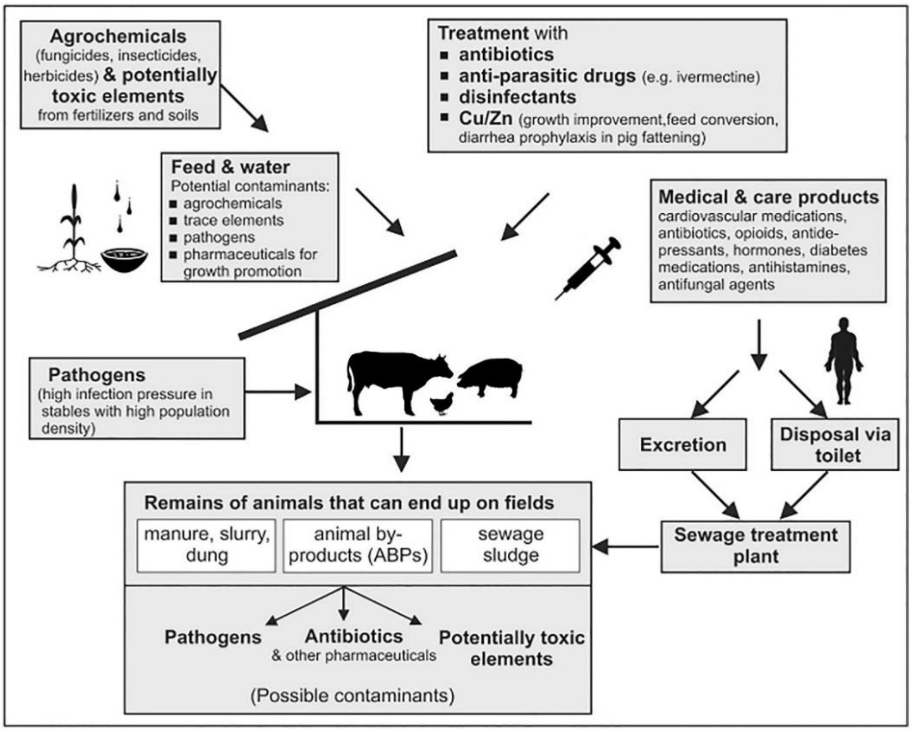

Figure 6: Potential contamination of recycling fertilizers (Bloem et al., 2017)

Whereas the struvite precipitation process effectively excludes pathogens and pharmaceuticals in the crystallization process. Also reported heavy metal contents are below legal or detection limits. Hence p-precipitation is considered a safe phosphorus recycling process (Muys et al., 2021). Also, bokashi poses a low risk of polluting effects on the environment or human beings.

The quality and safety are determined by the ingredients used. When including organic household waste the risk of applying plastic and other falsely disposed of materials to agricultural soils is high. Studies report that a high number and diversity of microbes contained in bokashi has a positive impact on the number of pathogens in the soil after application (Ghanem, El-Zabalawy, Mustafa, & Elbanna, 2017).

Conclusively the use of sewage sludge followed by bokashi and struvite poses the highest risk for environmental pollution and human health among the used recycling fertilizers in this model. This chapter should not belittle the risk of contaminants in recycling fertilizer but put it into perspective with the inherent risks of conventional fertilization practices. More research and technological improvements are necessary to enhance the load, handling and removal of pollutants in waste streams. Source separation in sanitation plays an immanent role in this regard (Larsen & Gujer Willi, 2013).

2.5. Mathematical programming

Linear programming (LP) or mathematical programming was introduced by the US military after the second world war to optimize their supply of equipment and has a wide range of applications (Dantzig, 1983). In general, it is used for a better understanding of complex systems and the underlying relationships of their components as well as replacing the trial and error approach. A mathematical model predicting the outcome of certain managerial decisions can thus save time and costs in a practical context (MirHassani, 2019). Furthermore, a rising global population evokes the need for higher levels of agricultural production with limited means. The challenge of optimal allocation of scarce resources in food production is essential and can be tackled by mathematical programming towards for example the optimal use of water, fertilizer, land, labour etc. (Singh, 2012). Typical applications are feed mix problems, the optimization of crop patterns and crop rotation, land allocation or irrigation use (Alotaibi & Nadeem, 2021). Mathematical programming is appropriate to connect economic and bio-physical dimensions of agricultural production (Heckelei Thomas & Britz Wolfgang, 2005). Hence, I chose an LP model to gain a better understanding of the potential and hurdles of the implementation of recycling fertilizers.

A mathematical problem consists in general of decision variables, constraints, parameters and objective function(s). Decision variables are to be determined by the model and act for the possible decisions to be made. Constraints introduce restrictions on the model and thus determine its framework. The underlying dataset is introduced via parameters that define the production level and interrelations. The objective function consists of decision variables and aims to maximize or minimize the for-instance profit or costs of the production while meeting the given constraints which can be induced by nature itself (MirHassani, 2019). The general function for an optimisation problem is:

$$\begin{gathered} Optimise\ \ f(x_1, x_2, \dots, x_n) \\ subject\ to\ \ g(x_1, x_2, \dots, x_n) = 0 \end{gathered}$$

where *f()* is the objective function with the decision variables x_n subject to the set of constraint equations *g()* (Blanco-Fonseca, Flichman, & Belhouchette, 2011).

There are a variety of different models and modifications in mathematical programming. Starting from linear/ non-linear programming models towards multi-objective, dynamic or positive programming. Multi-objective programming has the advantage to optimize a certain problem while taking different criteria such as environmental, production or economic aspects into consideration. It does so by combining linear programming with weighted goal programming (WGP). WGP clusters the present objectives using weights and thus gives different objectives a hierarchical order in the multi-objective function. Further, the implemented targets and conflict of interests can be seen as decision-making objectives rather than constraints (Galán-Martín, Vaskan, Antón, Esteller, & Guillén-Gosálbez, 2017; Prišenk et al., 2014).

2.6. Optimization modelling applications

The following chapter sheds light on the mathematical programming model formulation done by several previous studies in the field of agriculture and resource economics (see Table 3). Particular interest lies in the basic assumptions and constraints as well as in the implementation of (P-)fertilizer in economic models.

Table 3: Literature review

Author(s) and years	Research focus
Nordin Hj. Mohamad & Fatimah Said, 2011	Multi-year linear optimisation model aiming at maximizing total returns in a crop mix problem
Grames et al., 2019	A general equilibrium model to review the economic feedbacks of nutrient recycling in the Austrian phosphorus cycle
Klinglmair, Vadenbo, Astrup, & Scheutz, 2017	Linear optimisation to minimize and replace mineral P in Danish agriculture
Keplinger, K.O., & Hauck, L. M., 2006	Optimisation model to minimize manure application costs while considering the problem of excessive phosphorus in the soil
Osaki & Batalha, 2014	Linear farm planning optimization model to maximize revenues and minimize risk in Brazilian double-crop production systems
El-Shishiny, 1988; Graveline, Loubier, Gleyses, & Rinaudo, 2012; Siskos, Despotis, & Ghediri, 1994	Multi-objective programming farm optimization and the development of newly reclaimed lands
Graveline, Loubier, Gleyses, & Rinaudo, 2012	Introducing uncertainty via a Monte Carlo simulation to evaluate the impact of farming on water resources in a climate change context

The farmer's managerial challenge to decide what, how much and when to plant can be translated into a linear programming model**.** Nordin Hj. Mohamad and Fatimah Said (2011) utilize LP to obtain the maximum total returns for a six-period planning horizon in a crop mix problem in Bangladesh. Mixed-cropping systems in Bangladesh imply a variety of vegetables grown simultaneously during the season on one acre. The objective is to find the optimal combination of the vegetables considering the given constraints such as the availability of land or capital. The authors introduce some basic assumptions to avoid over-complexity in their model: the considered arable land is equal in quality and fertility, crop prices and yields do not change over time as well as equipment and amount of labour do not change over the planning horizon.

Grames et al. (2019) utilize a general equilibrium model to evaluate the impacts of economic decisions on the phosphorus resource cycle in a closed economy. The authors examine coupled feedback between economic decisions and environmental impact including households, crop production, animal husbandry and industry. The farmers in this model maximize their profit in the profit function which is built on a constant crop production technology. The P demand concluding from this crop production needs to be satisfied from the offered mineral or recycling P-fertilizer. Those are characterized by their price and P-availability in the soil. Phosphorus availability is considered by efficiency rates ranging from 0 to 1 (1 = full availability for mineral fertilizer). Costs for recycling fertilizer are estimated by considering the investment and operating costs for the underlying recovery technology. However, the soil organic matter content in recycling fertilizer and the resulting enhancement of soil fertility is not of concern in this study.

Klinglmair et al. (2017) carried out a linear optimisation of the Danish phosphorus flows to assess the optimal distribution of P. The objective of this optimisation is to minimize the imported mineral P fertilizer by implementing P from nutrient recovery processes like compost and sludge. The optimization model is carried out in GAMS and considers the P availability in the soil over three time periods. The study emphasizes that over time, the share of mineral fertilizer could be reduced even more due to the accumulation and gradual release of phosphorus. However, the authors do not implement any economic considerations such as prices or costs for the phosphorus recycling technology.

Keplinger, K.O., & Hauck, L. M. (2006) utilize linear programming to minimize manure application costs in areas with high manure production by optimal allocation subject to the nutrient requirements of the cropland. In their model manure application on cropland is dependent on transportation cost/distance, application costs, macronutrient content, nutrient availability and crop requirements. As manure application is often limited due to timing, weather and cultivation practices a maximum manure adoption rate (0,5) was introduced. Organic fractions of nutrients in manure become available over time and thus are subject to decay ratios. However, as annual manure application is assumed, steady-state nutrient availability coefficients for all fertilizers were considered. Furthermore, the overall value of manure is determined by the macronutrient value of N and P. Other potentially beneficial agronomic characteristics of manure such as micronutrients and organic matter content have a positive influence on yields and soil fertility are left out. Prices for mineral fertilizer are considered by looking at the five-year average farm prices for N and P respectively.

Among others, Osaki and Batalha (2014) introduced risk in their farm planning optimization problem. They emphasize that risk and uncertainty are significant factors inherent in crop production and should thus be considered. Otherwise, optimization models not including risk can lead to misleading or even unacceptable results. In their decision support model focusing on Brazilian double multiproduct farms risk is accounted for as deviations of the product gross margin over time. Further, the objective of the study is to minimize the deviations of crop contribution margins from the expected contribution margin over a ten-year time horizon. The expected contribution margin was derived from a linear regression of an underlying region-specific dataset.

In agricultural enterprises, a variety and often conflicting socio-economic objectives are of concern. Besides the economic prosperity of the agricultural production other goals such as environmental and pollution reduction related targets, the workload during the growing season or self-sufficiency is important. To comprehensively evaluate a farm's objective by utilizing multi-objective programming possess a great advantage in the development of agricultural enterprises. For instance, Siskos et al. (1994) use a multi-objective goal programming to solve a farm allocation problem in Tunisia with the objectives to maximize gross margin, employment and forage production while minimizing seasonal labour and tractor utilization. El-Shishiny (1988) employ the same technique to plan the development of newly reclaimed lands in developing countries to create permanent and attractive settlements. The conflict of interests, in this case, is in the sustainable utilization of local resources such as arable land and water while being economically viable.

Graveline et al. (2012) introduce uncertainty via a Monte Carlo simulation to evaluate the impact of agriculture on water resources in a climate change context. They depict the instability of the economic (micro and macroeconomic) and environmental (biophysical) framework of agricultural production and hence the changing impact it has on water resources. Among these uncertain parameters are subsidies, prices for agricultural products, inputs and climate conditions. By introducing the Monte Carlo simulation which produces a large number of different scenarios with randomly drawn values for the parameters and statistical analysis of the simulation results a more relevant decision making is possible.

3. Material and methods

In the material and methods chapter, I introduce the study area, chosen recycling concept and shed light on the general model formulation. Further, I introduce the data input for the linear programming model and resulting scenarios.

3.1. Study area – the Isle of Dordrecht

The Isle of Dordrecht (Figure 7) is located in the province of South Holland. The island, which covers around 10.000 ha, lies mainly below sea level and is surrounded by dikes. The east side of the island is encapsulated by the river "Nieuwe Merwede" which is an extension of the Waal. The island can be divided into urban, agricultural and Biesbosch nature conservation areas. The city of Dordrecht has a population of roughly 120,000 inhabitants (Hoss, Jonkman, & Maaskant, 2013). The agriculture at the Isle of Dordrecht is characterized by arable farming with no dairy and only extensive animal production (sheep farming).

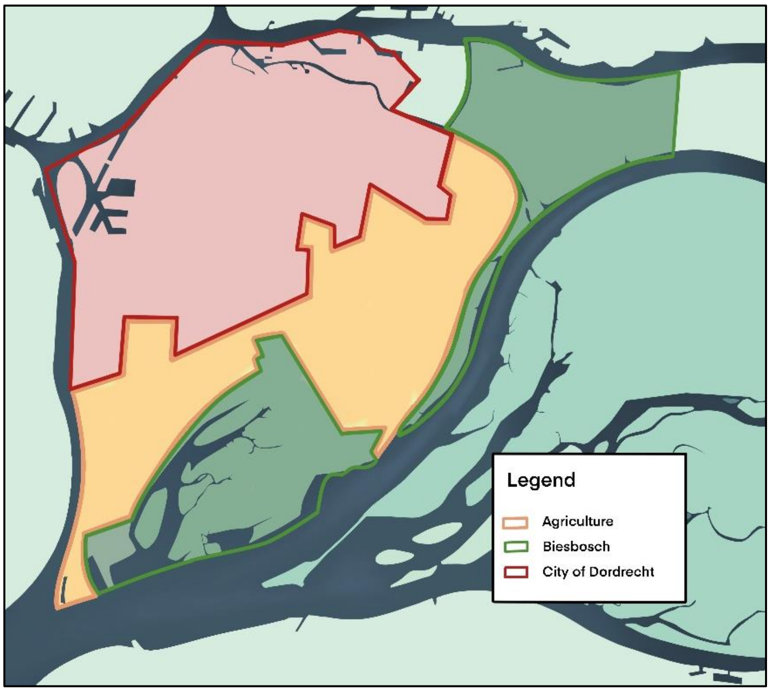

Figure 7: Map of the Isle of Dordrecht with agricultural, Biesbosch nature conservation and city area (own illustration).

The 1750 hectares of agricultural land are managed currently by 37 farmers growing 25 different types of crops (Heath Farm Foundation, (n.d.)). Table 4 presents the variety of crops grown over the last five years. Cereals including wheat, barley and rye take the main share of the arable land (47%), while potatoes (19%) and sugarbeet (15%) are the second and third most grown crops in this area (CBS, 2021a).

Table 4: Crop share at the Isle of Dordrecht (2017-2021) (CBS, 2021a)

Crop	**Year**					
	2017	2018	2019	2020	2021	Ø
Potatoes	21%	19%	20%	18%	15%	19%
Sugarbeet	16%	16%	15%	15%	15%	15%
Cereals	46%	47%	48%	45%	48%	47%
Vegetables	14%	14%	13%	14%	15%	14%
Others	3%	4%	5%	7%	7%	5%

This study area is of significant interest because of its multiperspective problem setting. Agriculture on the Isle of Dordrecht is under pressure from different aspects. On the one hand, the growing city and urbanization put the agricultural area under pressure from the north. The inhabitants of Dordrecht use this area mainly as a place for recreation. Further, the Biesbsoch nature conservation area has expanded in recent years; its concept of extensive natural management is contrary to intensive arable farming. Following this, the agricultural production on the Isle of Dordrecht is under pressure and faces a threat to be further narrowed down.

Therefore, the agricultural area, as well as the farmers, are interested in fostering a stronger ideologic as well as physical connection with the city of Dordrecht and the nature conservation areas to sustain their prospective position on the Isle. This is mainly brought forward by the "Foundation Heathland Farms Netherlands" and participating farmers. The underlying concept of the foundation is to implement the traditional infield-outfield farming system to reconnect the intensively cultivated agricultural areas (infields) with the outfields. Historically the outfields are extensively managed by grazing and serve as a nutrient supplier for the infields (Woestenburg, 2018). In combination with the philosophy of the Heath Farm Foundation, farmers at the Isle of Dordrecht participate in a bottom-up initiative to produce organic fertilizer such as Bokashi based on raw materials and waste from the urban as well as nature conservation areas (Woestenburg, 2019).

Based on this, the Isle of Dordrecht is a suitable research area to optimize the agricultural nutrient demand and nutrient supply by using recycling fertilizer from the surroundings to make agriculture less reliant on imported finite resources.

Nutrient recycling concept

The identified resources from the surrounding areas are biomass including green cuttings from the city's public green areas and Biesbosch conservation area, GFT as well as blackwater stemming from the city. This concept follows the philosophy of the *Heideboerderij* in which the local outfields like extensively managed meadows are utilized to supply the intensively managed agricultural production (Woestenburg, 2019). Further, these resources are processed by using anaerobic treatment and P-precipitation to produce hygenized sewage, bokashi as well as struvite. This nutrient recycling scheme illustrated in Figure 8 is based on Buckwell and Nadeu; Larsen and Gujer Willi; Wielemaker (2016; 2013; 2019).

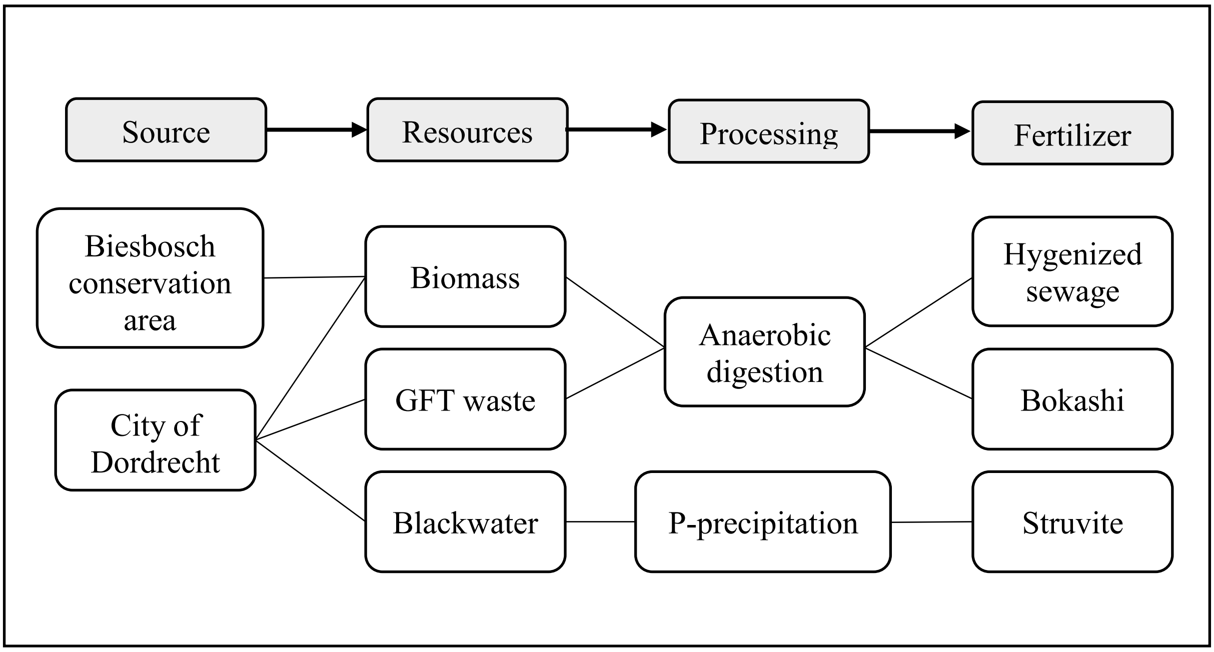

Figure 8: Resource recycling concept (own illustration)

Out of this recycling concept, the following maximum amounts of recycling fertilizer based upon resources from the outfields are estimated (Table 5). The amount of available resources is based on CBS; Wielemaker; Woestenburg (2021b; 2019; 2019). For the struvite nutrient recovery process I used a 30% recovery efficiency which lies in the middle of the reported minimum and maximum recovery rates for this technology (Muys et al., 2021).

Table 5: Recycling fertilizer from the outfields

Fertilizer		
Struvite	118	kg/ha/year
Bokashi	10	t/ha/year
Hygenized sludge	13	t/ha/year

This leads to a maximum available amount of struvite fertilizer of 118kg/ha/year. For bokashi and hygenized sludge, the values are at 10 and 13 t/ha/year respectively. These values are later used to estimate the overall extent of the optimal fertilizer and nutrient management on the Isle of Dordrecht.

3.2. Modelling approach

I chose a multi-objective linear programming model to depict the challenge and potential of implementing recycling fertilizer based on regional resources in the nutrient management of the agricultural production on the Isle of Dordrecht. This was realised in GAMS 36.1.0 which is a modelling environment for mathematical programming and optimization. The linear programming model aims at minimizing mineral fertilizer input – or maximizing input of recycling fertilizer – while satisfying plants' nutrient demands of the agricultural production in place. Further, fertilization costs are to be minimized. As fertilization management deals with long time horizons the linear programming model is spread over nine time periods each of which represents one growing season. Objectively the model tests the performance of recycling fertilizers against mineral fertilizer under agricultural production constraints.

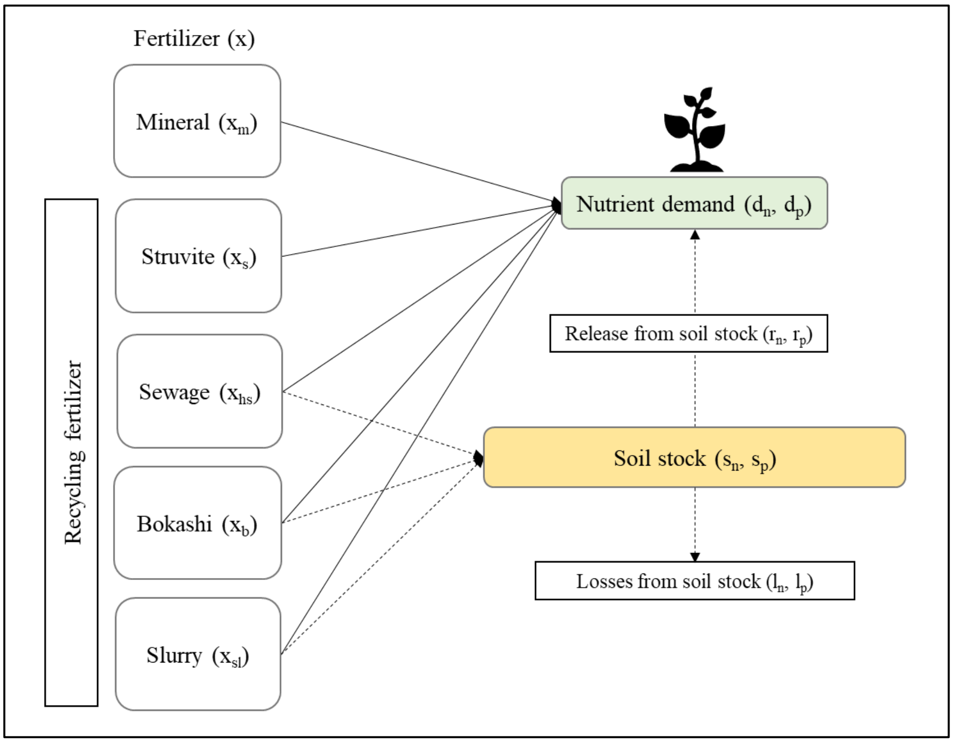

Figure 9: Multi-objective linear programming model

The nutrient demand on the Isle of Dordrecht was estimated from the premise that agricultural productivity and yields nee do be held constant. The plant's nutrient demands for nitrogen and phosphorus need to be fulfilled by the available fertilizers ($x_{m,st,b,hs,sl}$) which are, among others, the decision variables of the model. The fertilizers are characterized by nitrogen and phosphorus content ($c^{n,p}_{m,st,b,hs.sl}$), nutrient availability ($y^{n,p}_{m,st,b,hs.sl}$) as well as price ($p_{m,st,b,hs,sl}$). Other decision variables include soil nutrient stock (s^n, s^p) as well as total discounted cost (c_{total}). It is assumed that the farmer takes the storage capacity of his soil into account while deciding upon the nutrient management of his crops. Although nutrient dynamics in the soil are highly dependent on environmental factors and thus hard to predict for the farmer it is his managerial choice how he utilizes the soil for plant production and fertilization. Thus, the nitrogen and phosphorus soil stock are considered variable in this model. Furthermore, the farmer in this model wants to minimize his fertilization costs, which is reflected in the objective function as well. The total costs are calculated by summing up the discounted costs for fertilization over each period.

The agronomic considerations constraining the model are the nutrient demand (min and max) as well as maximum adoption rates for fertilizer technologies. First, the nutrient demand for phosphorus and nitrogen for the three major crops on the Isle of Dordrecht: Wheat, potatoes and sugarbeet (CBS, 2021a) are considered. The plant's nutrient demand is further approached from two sides. At first the minimum fertilization application to deliver enough available nutrients to sustain the assumed yields. Secondly, the allowed fertilization limits for nitrogen and phosphorus on arable land according to the regulation (Uitvoeringsregeling meststoffenwet, 2014) cannot be exceeded (maximum application).

Nutrients which are bound in organic compounds and not available in the first period after application are stored in the soil stock and released continuously in the following periods (similar to Klinglmair et al., 2017). This means that all organic recycling fertilizers (bokashi, sewage and slurry) contribute to the soil stock while the nutrients in mineral and struvite fertilizer are directly taken up by the plants. Periodically 40% of the phosphorus and 90% of the nitrogen in the soil stock is released and accounted for in the nutrient demand. Additionally, nutrient losses from the soil stock due to leakage and denitrification are taken into account. As phosphorus is less prone to leakage and outgassing only 4.5% of losses are assumed, while 8% of nitrogen is assumed to be lost per period (Baumgärtel, Ebertseder, & Gutser, 2003; Zoboli, Laner, Zessner, & Rechberger, 2016).

Further, for bokashi and sludge, it is assumed that due to technical application limitations and other agronomic considerations only 50% of the demanded nitrogen can be met (adoption rate). For example, cause of their physical characteristics application is only possible as long as no crops are grown on the field (Keplinger, K.O., & Hauck, L. M., 2006).

The Monte Carlo simulation was carried out following the PERT methodology (Davis, 2008). By choosing a minimum, maximum and most likely value (mean) for every parameter the variance was calculated (Eq. 1). Based on this the shape distributions alpha (α) and beta (β) were estimated (Eq. 2+3). If α and β are equal to 4 the parameter is symmetric. Differing values indicate that the parameter is skewed to the right or left. With this information for every parameter, a beta-pert probability distribution with 10,000 random values was drawn.

$$\sigma^2 = \frac{(b-a)^2}{36} \qquad \text{Eq. (1)}$$

$$\alpha = \left(\frac{\mu - a}{b - a}\right)\left[\frac{(\mu - a)(b - \mu)}{\sigma^2} - 1\right] \qquad \text{Eq. (2)}$$

$$\beta = \left(\frac{b - \mu}{b - a}\right)\left[\frac{(\mu - a)(b - \mu)}{\sigma^2} - 1\right] \qquad \text{Eq. (3)}$$

I calculated the variance, alpha and beta values in excel. Also, the random values were created using the BETAINV(Wahrsch;Alpha;Beta;[A];[B]) function in excel. The excel sheet containing 10,000 random values for each of the model used parameters was passed on to GAMS and used as input for each iteration.

3.3. Model formulation

To investigate the optimal substitution between mineral fertilizer by recycling fertilizer in the given case study area I formulated a weighted multi-objective **goal function** which maximizes utility by minimizing mineral fertilizer input – or maximizing recycling fertilizer input – and minimizing total discounted fertilization costs over nine time periods respectively (Eq. 4). The weights w_1 and w_2 distribute the contractionary preferences between minimizing mineral fertilizer and minimizing costs.

$$U = -w_1 \times \sum_{t=1}^{10} x_m - w_2 \times \sum_{t=1}^{10} c_{total} \qquad \text{Eq. (4)}$$

Total costs per period are calculated by summing up the costs per used fertilizer discounted with the discount rate *d* (Eq. 5).

$$c_{total} = \frac{\left(\sum p_{m,st,b,hs,sl} \times x_{m,st,b,hs,sl}\right)}{(1+d)^{t-1}} \qquad \text{Eq. (5)}$$

The model is **constrained** by functions for the minimum nutrient demand for available nutrients $d_{min}^{n,p}(t)$ (Eq. 8+9) and maximum fertilizer application rates $d_{max}^{n,p}(t)$ (Eq. 6+7). Maximum application rates consider the fertilizer amount $x_{m,s,b,hs,sl}$ times nutrient content $c_{m,s,b,hs.sl}^{n}$ while nutrient availability includes nutrient release from the last period's soil stock $s^{n,p}(t-1) \times r^{n,p}$ and available nutrients from the fertilizers applied.

$$\sum x_{m,st,b,hs,sl} \times c_{m,st,b,hs.sl}^{n} \le d_{max}^{n}(t) \qquad \text{Eq. (6)}$$

$$\sum x_{m,st,b,hs,sl} \times c_{m,st,b,hs.sl}^{p} \le d_{max}^{p}(t) \qquad \text{Eq. (7)}$$

$$s^{n}(t-1) \times r^{n} + \sum x_{m,st,b,hs,sl} \times c_{m,st,b,hs.sl}^{n} \times y_{m,st,b,hs.sl}^{n} \ge d_{min}^{n}(t) \qquad \text{Eq. (8)}$$

$$s^{p}(t-1) \times r^{p} + \sum x_{m,st,b,hs,sl} \times c_{m,st,b,hs.sl}^{p} \times y_{m,st,b,hs.sl}^{p} \ge d_{min}^{p}(t) \qquad \text{Eq. (9)}$$

The maximum adoption for bokashi (Eq. 10) and hygenized sludge (Eq. 11) is described by the following two constraints so that they cannot exceed 50% of the maximum demanded nitrogen and phosphorus. This limits the application to a maximum of 35 tonnes and 28 tonnes per period for bokashi and hygenized sludge respectively. For sludge, this goes in line with the recommended maximum application rate of the Germany Sewage Sludge Ordinance (1992) which recommends a maximum of 100 t/FM in three years.

$$x_b \times c_b^{n} \le 0.5 \times d_{max}^{n}(t) \qquad \text{Eq. (10)}$$

$$x_{hs} \times c_{hs}^{n} \le 0.5 \times d_{max}^{n}(t) \qquad \text{Eq. (11)}$$

The soil stock for nitrogen and phosphorus is depicted in Eq. 12 and 13. The nutrient content is dependent on the amount of organic fertilizer $x_{b,hs,sl}$ applied in the previous period and their corresponding nutrient availability $y^{n,p}_{b,hs,sl}$. Also, the release rate $r^{n,p}$ and nutrient losses $l^{n,p}$ are considered.

$$s^n(t) = s^n(t-1) \times (1 - r^n) - (s^n(t-1) \times l^n) + \sum x_{b,hs,sl}(t-1) \times \left(1 - y^n_{b,hs,sl}\right) \times c^n_{b,hs,sl} \quad \text{Eq. (12)}$$

$$s^p(t) = s^p(t-1) \times (1 - r^p) - (s^p(t-1) \times l^p) + \sum x_{b,hs,sl}(t-1) \times \left(1 - y^p_{b,hs,sl}\right) \times c^p_{b,hs,sl} \quad \text{Eq. (13)}$$

3.4. Data

Baseline

The bemestingsplan (fertilization plan) of one farmer from the Isle of Dordrecht serves as the baseline for the model. His fertilization plan contains information about the nutrient management of every crop grown on his farm. Based on this the share of mineral and organic fertilization throughout his crop rotation was estimated (Table 6). Overall the majority (65%) of nitrogen is supplied by mineral fertilizers while phosphorus mainly (73%) stems from organic fertilization. The farmer uses solely cattle slurry imported from the region nearby as organic fertilizer.

Table 6: Share of nutrients

	Nitrogen	P_2O_5
Mineral	65%	27%
Organic	35%	73%
Fast available	83%	63%
Slow available	17%	37%

Also, the share of fast and slow available nutrients was estimated by assuming that 50% of nitrogen and phosphorus stemming from organic fertilizer is available in the year of application (Wendland, Diepolder, Offenberger, & Raschbacher, 2018). Based on these figures it is assumed that the corresponding nutrient demands especially the demand for fast available nitrogen (83%) and phosphorus (63%) need to be satisfied to sustain the current level of yields.

Table 7: Maximum and minimum application rates

	Maximum		Minimum	
	N	P_2O_5	N	P_2O_5
Potatoes (periods 1,4,7)	250	120	206	76
Wheat (periods 2,5,8)	245	70	202	44
Sugarbeet (periods 3,6,9)	150	80	124	51

This leads to minimum nitrogen and phosphorus application rates for the three major crops wheat, potatoes and sugarbeet with an average of 178 kg N/ha and 57 kg P_2O_5/ha. These values serve as the minimum application rates for the linear programming model starting at period one with the nutrient demand of potatoes, period 2 the nutrient demand of wheat and so on. The maximum rates for each crop stem from the Dutch legislation. The highest application rate has potatoes with 206 kg of nitrogen and 76 kg of phosphorus.

The fertilizer characteristics are based upon literature as well as on side testing results. Diammonium phosphate (DAP) and urea represent the mineral fertilizer in the model. DAP is a common nitrogen (18%) and phosphorus (46%) fertilizer while urea contains solely nitrogen (46%). The prices for DAP and urea are average prices over the last ten years taken from WorldBank data. The prices of the recycling fertilizers are solely based on their nutrient (N+P) content and the individual nutrient price derived from the mineral fertilizer (0,57 €/kg N; 0,69 €/kg P_2O_5). The mineral fertilizers diammonium phosphate and urea stand out with the highest price per tonne. However, considering the comparably low nutrient contents and nutrient availability of the recycling fertilizer the price of the mineral fertilizer is far more competitive.

Table 8: Fertilizer characteristics

	DM (%)	N (%)	P2O5 (%)	Organic matter	Price (€/t FM)
Diammophosphat (DAP)	100.0%	18.0%	46.0%	0%	360
Mineral (urea)	100.0%	46.0%	0.0%	0%	264
Struvite	100.0%	5.0%	28.0%	0%	227
Bokashi	59.5%	0.52%	0.22%	15.8%	2.7
Hgyenized sludge	5.0%	3.60%	3.2%	62.5%	2.1
Slurry	7.5%	3.20%	2.3%	62.9%	2.6

* Nutrient and organic matter content per dry matter, USD to € conversion rate 0.92, DAP and urea are based upon 10 years' average prices

The nutrient contents of bokashi and slurry are taken from sample collections of the participating farmer. Bokashi yields very low nutrient contents and is thus more a soil conditioner than a proper fertilizer (comparable with compost). The values for hygenized sludge were taken from Bayerische Landesanstalt für Landwirtschaft (2018) having roughly similar values compared to slurry. Full nutrient availability (Table 9) is assumed for mineral and struvite fertilizer while the nutrients in the organic fertilizer are only partially available during the period of application (Wendland et al., 2018). For bokashi, only 20% of the applied nutrients are available in the first year. Hygenized sludge and slurry have higher availability shares with 30 and 50% for nitrogen and 60 and 70% for slurry respectively.

Table 9: Nutrient availability

	N (%)	P2O5(%)
Diammophosphat (DAP)	100%	100%
Urea	100%	100%
Struvite	100%	100%
Bokashi	20%	20%
Hgyenized sludge	30%	60%
Slurry	50%	70%

The **baseline** of this model contains solely mineral fertilizer x_m and slurry x_{sl} as input (decision) variables while it is assumed that the latter one can deliver a maximum supply of 30% of demanded nitrogen. Further, the model minimizes mineral fertilizer and total discounted costs while the parameter baseline values have been used. The weights w_1 and w_2 are set to 0.4 and 0.6 respectively. While farmers' ambitions to substitute mineral fertilizer by recycling fertilizer are high, economic considerations are proven to be the basis of decision-making in this regard (Hijbeek et al., 2018). This baseline mimics the current situation of a farming enterprise on the Isle of Dordrecht. After the baseline scenario the recycling fertilizer $x_{s,b,hs}$ are added to the model and run at their baseline values (**scenario 1**).

Uncertainty

Uncertainty enters the model at different points and plays a decisive role in nutrient management decision-making. I want to add to this by depicting the conflict of interest between reliability and uncertainty between mineral and organic fertilizer. Following this idea, I use the Monte Carlo approach by drawing random values for the used parameters. While some parameters are highly uncertain having a wide range between minimum and maximum other are more certain and reliable. For each parameter, a distribution probability histogram can be drawn.

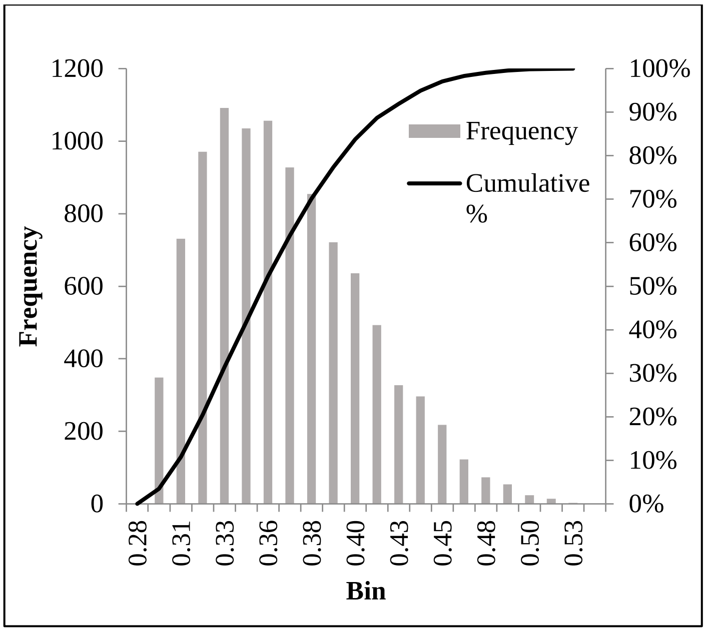

Figure 10: Histogram of parameter distribution DAP price (€/kg)

Figure 10 presents the distribution probability of the parameter DAP price (€/kg). With the median (0.35€) being smaller than the average (0.36€) the probability distribution is skewed to the right. The standard deviation (SD) is 0.044 €/kg. In the following, I will introduce the database backing up the beta-pert distributions of the parameters.

Prices

Fertilizer market prices are influenced by several factors like fossil energies or geopolitical situations (especially phosphorus) and thus are changing over time (Cordell et al., 2009). Table 10 illustrates the assigned prices I have used in my model as well as their minimum, maximum, alpha and beta value which describe their uncertainty. For DAP the minimum price over the last ten years (2012-2021) lies at 283 €/t peaking at a maximum of 550 €/t in 2021. For urea, the minimum and maximum prices are 190 €/t and 442 €/t respectively (WorldBank, 2022). As the fertilizers used for the model are to a certain degree substitutable I assume the price development for the recycling fertilizer to be alike the mineral ones. Struvite as the most similar fertilizer to the mineral ones has a price range spreading from 179 €/t to 347 €/t. This goes in line with the prices for commercially available struvite reported by (Muys et al., 2021).

Table 10: Fertilizer prices (€/kg FM) and distribution

	Min	Baseline	Max	Alpha	Beta
Mineral (DAP)	0.283	0.360	0.550	1.82	4.54
Mineral (urea)	0.190	0.264	0.442	1.90	4.57
Bokashi	0.000	0.003	0.003	1.80	0.18
Hygenized sludge	0.000	0.002	0.003	3.81	0.95
Struvite	0.179	0.227	0.347	1.79	4.52
Slurry (cattle)	0.000	0.003	0.003	3.81	0.95

For the organic recycling fertilizer slurry and hygenized sludge, I assumed e a maximum price increase from the baseline of 25%. For Bokashi as the least substitutable fertilizer – due to nutrient composition and technical application constraints – I assumed a modest price increase of 10% resulting in a maximum price of 2.93 €/t/FM. The minimum prices for slurry, hygenized sludge and bokashi are zero. Due to the surplus production of animal manure and slurry in the Netherlands in some regions, farmers have to pay to get rid of their manure (Wageningen UR Livestock Research, 2014). Furthermore, the biomass used currently on the Isle of Dordrecht to produce bokashi is also free of cost. The resulting costs are discounted at a rate of 4%. The full corresponding table is given in Appendix B.

Nutrient content and availability

Mineral fertilizer production follows standardized production procedures hence given nutrient values are reliable. Thus, I assume no variation in the nutrient content and nutrient availability for DAP and urea. The same holds for the commercial-produced recycling fertilizer CrystalGreen® (struvite). Organic fertilizer however underly great variability in their nutrient composition as well as their form. The final composition is highly dependent on the type of animal, feeding, farming system, processing or in the case of bokashi raw materials used (Williams, Guidi, & Hermite, 1985). In cattle slurry I assumed the nutrient content to be varying from 1.9 to 3.8 kg/t/FM for nitrogen and 1 to 2.3 kg/t/FM for phosphorus (Williams, Guidi, & Hermite, 1985).

For bokashi, the nutrient content is specifically dependent on the raw materials used for anaerobic digestion. Thus, the range is expected to be comparatively high ranging from 1.8 to 10 kg/t/FM for nitrogen and from 0.45 to 0.9 kg/t/FM for phosphorus (Quiroz & Céspedes, 2019). The in the literature reported values for digested sludge range from 0.8-3 kg/t/FM nitrogen and 0.75 to 2 kg/t/FM phosphorus for one tonne of treated sewage (Fytili & Zabaniotou, 2008).

As high amounts of nutrients in organic fertilizers are bound in organic compounds their availability is highly dependent on the mineralization process during the growing season. Thus, for cattle slurry, the phosphorus availability varies between 46% and 94% in the first year of application. The nitrogen availability is significantly lower at 30 to 69% (Eghball, Wienhold, Woodbury, & Eigenberg, 2005). I assumed a similar variation in nutrient availability for hygenized sludge. For bokashi, the variation in nutrient availability is closer to compost. About 20% of nitrogen and phosphorus are available in the first year of application with a variation of 5% upwards and 5% downwards from the initial baseline value (Bayerische Landesanstalt für Landwirtschaft, 2018).

To account for the variability and uncertainty of the nutrient behaviour and decomposition processes in the soil stock the related parameters are also part of the Monte Carlo simulation. For nitrogen, the release rate from the soil stock ranges from 80 to 100%, while 5-10% are lost per period. The annual release rate for phosphorus ranges from 30 to 50% while 3 to 6% is lost (Blume et al., 2016).

Implicit cost scenario

In **scenario 3** I want to emphasize the benefits of organic fertilizers compared with mineral fertilization. Therefore I use the concept of implicit cost which is by definition costs determined by the value of the next best opportunity that does not require a money payment (Mankiw, 2020). I do this by implementing implicit costs of using mineral fertilizer to satisfy plants' nutrient demands and thus forego the benefits of utilizing organic fertilization for this purpose. The beneficial values of high organic matter supply and content in the soil are manifold including direct and indirect ecosystem services (Sparling, Wheeler, Vesely, & Schipper, 2006). It is essential for soil fertility, increased microbiological activity in the soil and erosion control (Blume et al., 2016; Fytili & Zabaniotou, 2008). Further, the nutrient and water holding capacity as well as release are increased (Hudson, 1994). A high organic matter content can also reduce the risk of yield losses due to drought. Additionally, the accumulation of organic matter in the soil and sequestration of carbon creates the opportunity to acquire carbon credits (carbon farming) (Sharma, Kaushal, Kaushik, & Ramakrishna, 2021).

I consider all these foregone benefits when accounting for implicit costs of the usage of mineral fertilization. I approximated the implicit cost by assuming the farmer must decide between supplying one kilogram of nitrogen –the most important and decisive nutrient – from mineral or organic fertilization. Resulting in an implicit cost of 0.015€ per kg nitrogen stemming from mineral nitrogen for the baseline value. The minimum and maximum values are assumed to be 0.009 and 0.037 €/kg. Underlying figures for the value of soil organic matter are taken from Sparling et al., 2006; USDA, (n.d.). The complete approximative calculation can be found in Appendix C.

As the Netherlands imports excessive amounts of nitrogen and phosphorus via feedstuff for livestock and thus is highly dependent on foreign resources I decided to implement one scenario in which slurry is not considered as recycling fertilizer. Further, it is to say that as there is no animal production on the Isle of Dordrecht and slurry needs to be transported from regions with nutrient surplus nearby. Hence in **scenario 4,** I introduce the target to minimize slurry as well as to further reduce dependence. I do this by adjusting the objective function as follows:

$$U = -w_1 \times \sum_{t=1}^{9} x_m - w_2 \times \sum_{t=1}^{9} x_{sl} - w_3 \times \sum_{t=1}^{9} c_{total} \qquad \text{Eq. (14)}$$

However, the main objective to minimize mineral fertilizer has a higher relevance than minimizing slurry. Hence the weighting factors are adjusted in the following manner $w_1 = 0.3$; $w_2 = 0.1$; $w_3 = 0.6$. All other constraints stay in place.

All scenarios and characteristics are collected in Table 11. The model results were passed on from GAMS to excel for further evaluation.

Table 11: Scenarios and their settings

Scenario:	Settings:
Baseline	All parameters at their baseline values, struvite, bokashi and hygenized sludge are not included
Scenario 1	Struvite, bokashi and hygenized sludge fertilizer are added to the model at their baseline values
Scenario 2	Uncertainty is introduced via Monte Carlo simulation
Scenario 3	Implicit costs are added
Scenario 4	Changing the objective function, aiming at minimizing mineral and slurry fertilizer

4. Results

In the results section, I will present the main findings of the fertilizer optimization model. As the model is put together from scenario to scenario I will compare each scenario with the previous one. The main indicators for each scenario are presented in Table 12 while the full results for all variables are given in Appendix H-L.

Table 12: Results of the scenario-based modelling

	Total applied N	Total applied P	Recycling N %	Recycling P %	Costs €
Baseline	186.09	63.17	35.53%	73.91%	128.78 €
	+0.82	+8.95	+28.90%	+26.09%	+9.55 €
Scenario 1	186.91	72.13	64.42%	100.00%	138.33 €
	+1.18	+0.51	-3.84%	0.00%	-2.91 €
Scenario 2	188.10	72.63	60.59%	100.00%	135.41 €
	+0.02	+0.05	+0.01%	0.00%	+1.23 €
Scenario 3	188.12	72.69	60.60%	100.00%	136.64 €
	-4.31	-7.09	-17.20%	0.00%	-1.65 €
Scenario 4	183.80	65.59	43.41%	100.00%	134.99 €

In the baseline scenario, an average of 186 kg N and 63 kg P are applied over the nine periods. Overall 36% of the applied nitrogen and 74% of the applied phosphorus stemmed from recycling sources. The average discounted costs yielded 129€ with a maximum of 198€ in period 1 and a minimum of 70€ in period 9.

After introducing the recycling fertilizer struvite, bokashi and hygenized sludge the share of recycling nitrogen and phosphorus increased by 29 and 26% respectively. For phosphorus, the total demanded P was supplied from recycling fertilizer (100%) over all nine periods. For nitrogen, this was only possible in the last period, yet the overall amount of applied nutrients is rather low in period 9. In line with this, the total amount of applied phosphorus increased significantly by 9 kg per period compared to the baseline scenario while the increase in nitrogen was moderate at 0.8 kg.

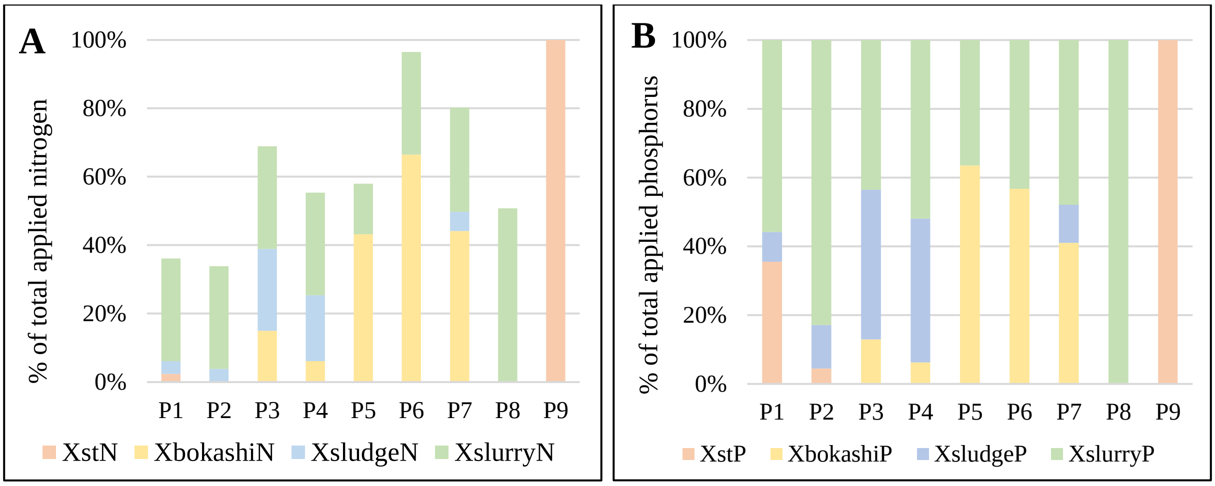

Figure 11: Recycling fertilizer input in scenario 1 **A**: share of total nitrogen stemming from recycling fertilizer per period; **B** share of total phosphorus stemming from recycling fertilizer per period

As depicted in Figure 11 the predominant amount of recycling nitrogen came from slurry followed by bokashi, sludge and struvite. Especially in the first two periods corresponding to the high nutrient demand of potatoes and wheat the share of recycling nitrogen is rather low (36 and 34%). However, with increasing periods the share of recycling fertilizer is increasing. Similar to nitrogen the majority of the applied phosphorus stemmed from slurry followed by bokashi, sludge and struvite. Furthermore, total discounted costs were increasing on average by 10€ with a maximum of total costs of 209€ in period 1 and a minimum of 5€ in period 9.

In **scenario 2** I introduced uncertainty into the model via the Monte Carlo simulation. Likewise, the input probability distribution of the parameters of each variable produces 10,000 values for each iteration which can be summarized in a histogram. As it is not possible to display all probability distributions for the variables I exemplary showcase the analysis of the share of nitrogen stemming from recycling fertilizer in periods 1 and 4 (corresponding to the nitrogen demand of potatoes) and the amount of urea and slurry applied in period 7.

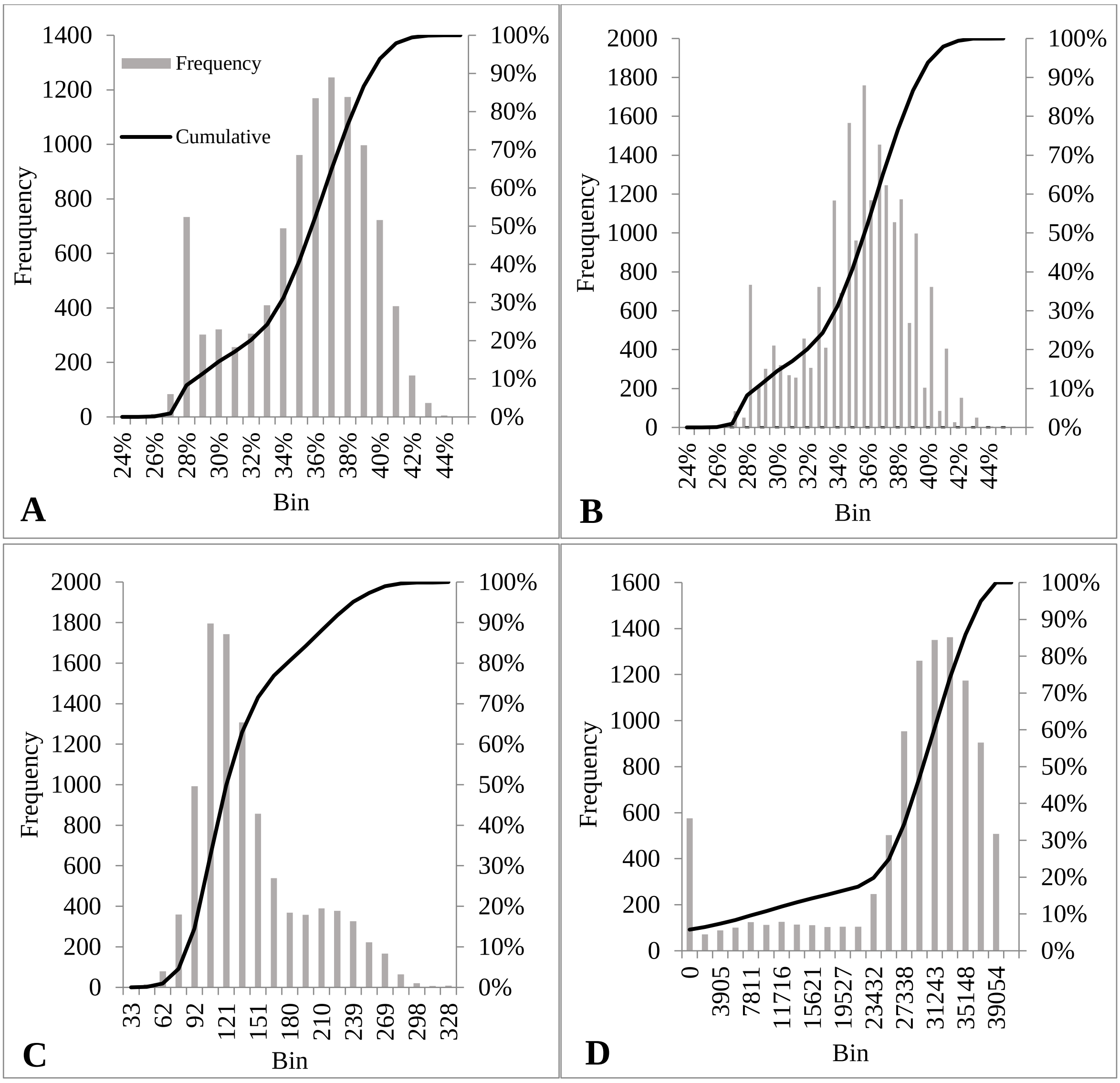

Figure 12: Histograms of decision variables in scenario 2: Recycling nitrogen shares in periods 1 (**A)** and period 4 (**B)**, amount of applied urea (**C**) and slurry (**D**) in period 7.

Figure 12 presents the belonging probability distributions. The distribution of the recycling nitrogen shares in period 1 (Figure 12a) is multimodal with the minimum and maximum values at 24% and 44% respectively. As the median (36%) is larger than the mean (35%) the distribution is skewed to the left. The standard deviation is 3.9%. Mode 1 is located at 37% while the smaller peak (mode 2) lies at 28% indicating another optimal solution at this value. This is also indicated by the bend in the cumulative distribution function at mode 2. Further, the negative kurtosis points to flat tails of the distribution with high amounts of values close to the average value (platykurtic distribution). Additionally, with a small 95% confidence interval (CI) of 0.08% indicating that the value of the variable lies between 35.02% and 34.87% the estimation is robust and reliable.

Similar to period 1 the variable in period 4 shows a bimodality but to a lower extent. Meaning that mode 2 has a lower probability compared to mode 2 in the distribution of the variable in period 1. The distribution has a minimum of 39% and a maximum of 68%. The median lies at 55 % while the average is at 54% which indicates a distribution skewed to the left. The kurtosis is positive pointing to a leptokurtic distribution with a sharp peak and more values in the tails. With 0.07% and 3.8%, the 95% CI and standard deviation are smaller compared to period 1. Due to the small 95% CI and standard deviation the values of the variables are robust and precise evoked by the number of iterations of the Monte Carlo simulation.

Figure 12c and b present the probability distribution of the amount of urea and slurry applied in period 7. For urea, the mean is 136 kg with the median 121 kg indicating a skewness to the left. The optimal values range from 33 to 328 kg while the 95% CI is between 136.94 and 134.99 kg. The number of applied slurry averages at 26841 kg with a standard deviation of 10060 kg and a 95% CI of 197 kg. The bimodal probability distribution is skewed to the left with mode 1 around 31000 kg and mode 2 at 0. Mode 2 has a probability of 5% indicated by the cumulative probability distribution.

The main result of introducing uncertainty in scenario 2 is that the share of nitrogen satisfied from recycling fertilizer drops by 3.8% (phosphorus is still supplied to 100% from recycling fertilizer in all periods). This is accompanied by a slight increase in the applied amounts of urea (+9.5 kg), struvite (+16.7 kg) and sludge (+4920 kg), meanwhile, the applied amounts of slurry (-2558 kg) and bokashi are reduced (-2788 kg). Also, like in scenario 1, the total amount of N and P is slightly increasing.

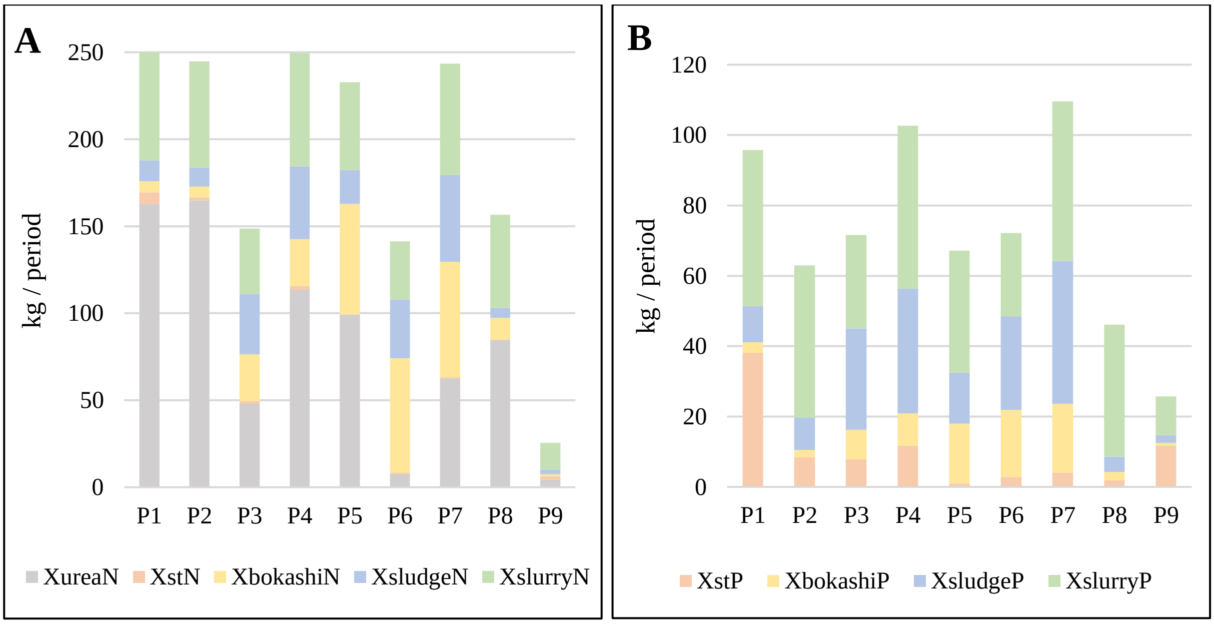

Figure 13: Applied nitrogen (**A**) and phosphorus (**B**) by fertilizer in scenario 2

In periods 1 and 2 urea supplies the highest amounts of nitrogen with about 163 and 165 kg while the application is slightly decreasing over the remaining periods. For potatoes, the amount of nitrogen supplied by urea is dropping to 114 kg in period 4 and 63 kg in period 7. The same holds for the applied urea in wheat and sugarbeet. With decreasing urea, the amount of bokashi (6 to 66kg) and sludge (from 12 to 50kg) is increasing over time.

The amount of phosphorus supplied to potatoes is slightly increasing over time from 96 (P1) to 103 (P2) and 110 kg in period 7. The same holds for the total applied P for wheat and sugarbeet in the first two repetitions. This is to the fact that the amount of bokashi which has low nutrient availability is increasing while the amount of struvite with high nutrient availability is decreasing. Hence overall more phosphorus is applied to satisfy the demand for available phosphorus. The overall discounted costs are reduced on average by 2.9€ per period compared to scenario 1.

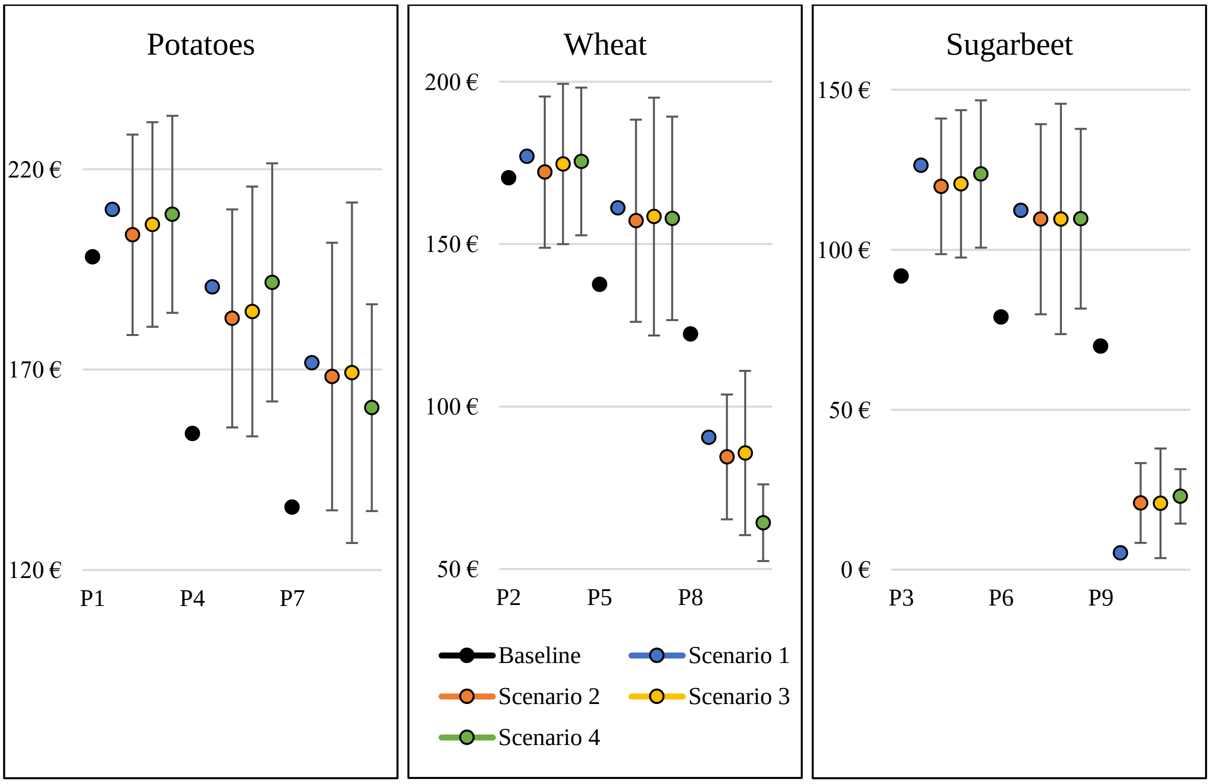

Figure 14: Discounted costs per period and crop, SD displayed for scenarios 2,3 and 4

Due to the high number of iterations of the Monte Carlo simulation the confidence interval is small for total discounted costs. For example, the 95% confidence interval of total discounted fertilization costs ranges from 0.24 in period 9 to 0.65 in period 7. This emphasizes that with a probability of 95% the real total discounted costs are between 167.63-168,93€ and 21.08-20.59€ for periods 7 and 9 respectively. The corresponding standard deviation is 12.46 and 33.38 for periods 9 and 7. Furthermore, the total fertilization costs per period are decreasing with time. In scenario 2 the fertilization costs for wheat decrease by 15€ and 73€ between periods 2, 5 and 8. This is only partially to be explained by the effect of discounting over time, but also due to the lower application of costly mineral fertilizer and struvite over time.

This goes in line with the increase in nutrients stored and released from the soil stock periodically. Starting with a soil stock assumed to have zero nutrients stored in all scenarios the soil stock accumulates nitrogen and phosphorus over time (see Figure 15).

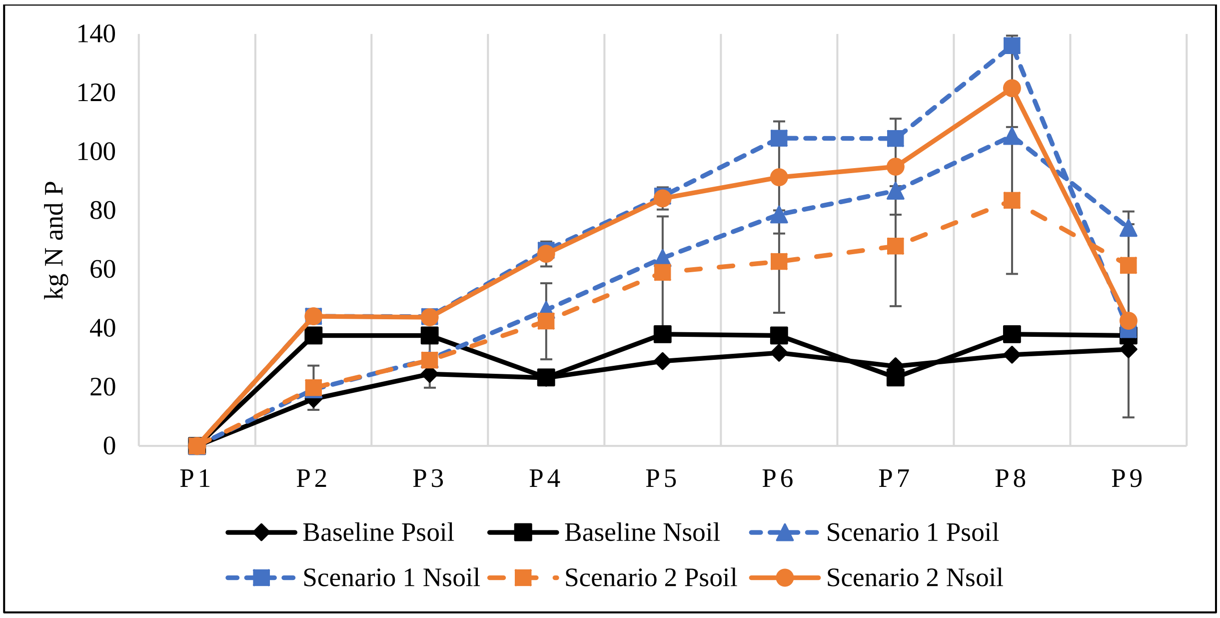

Figure 15: Nutrient soil stock

In the baseline scenario, the soil stock is used the least and stores a maximum of 38 kg nitrogen and 33 kg phosphorus over time. The highest utilization is to be found in scenario 2 where a maximum of 136 kg nitrogen and 105 kg phosphorus is stored. This leads to the fact that almost the entire nutrient demand for period 9 was satisfied by nutrients released from the soil stock (Appendix G illustrates the nutrient release and losses over time). However, with the slight increase of mineral and struvite fertilizer used in scenario 2 which do not contribute to the accumulation of nutrients in the soil stock the nutrient storage capacity is less utilized. The confidence intervals for the nutrient soil stocks are also small which indicates a high reliability of the presented variable values. For instance, the 95% CI for the phosphorus soil stock in period 8 is at 0.49 kg resulting in an upper limit of 83.90 and a lower limit of 82.92 kg P with a standard deviation of 25.96 kg P. The nitrogen and phosphorus soil stock in scenario 4 only deviates by a small margin from the figures in scenario 2.

Introducing implicit cost for the usage of mineral N fertilizer in **scenario 3** has no significant influence on the number of fertilizers used. The increase of 0.01% in the share of recycling nitrogen input proves to be not significant as the double-sided t-test scores a p-value >0.05 in each period (see Appendix E). However, the implicit costs per period account for 1.26€ while there is an overall increase in the total discounted cost of 1.23€. The remaining difference in costs is due to slight changes in the amounts of applied recycling fertilizer. These changes appear to be significant from period to period, for example in period 6 the amount of hygenized sludge decreases by 525 kg from scenarios 2 to 3. Though comparing the average application values over all periods, the changes are insignificant with a p-value of 0.98 (two-tailed t-test). However, the aim to accumulate organic matter in the soil is important and shows a slight increase in scenario 3 compared to scenario 2 (+ 8 kg per period). In the baseline scenario, 1268 kg organic matter solely provided by slurry was applied. Scenario 1 yields an average of 2498 kg of organic matter per period the highest application rate, followed by scenario 3 (2277 kg) and scenario 2 (2269 kg). In scenario 4 only 1988 kg organic matter is applied.

With experimentally increasing the implicit costs by adding 2€ the amount of recycling fertilizer is decreasing. This is to be explained by the strong emphasis on costs in the objective function. When implicit costs are added for every kg of nitrogen applied costs are increasing. To offset this additional cost, it is cheaper to reduce the amount of recycling fertilizer and increase mineral fertilization costs. In my model, the implicit costs for mineral fertilization need to exceed the costs of supplying 1 kg of available nitrogen based on recycling fertilizer to show a significant effect.

In **scenario 4** I considered slurry, not as a recycling fertilizer and changed the objective function accordingly. This results in a decrease of 17.2% for nitrogen stemming from recycling sources and an average increase of applied urea by 43 kg per period. Phosphorus is further supplied to 100% from recycling fertilizer over all periods. The application of slurry drops to zero over all periods and is offset by an average increase per period of bokashi (+6053 kg), struvite (+51 kg) and hygenized sludge (+3360 kg).

In the next step, I evaluated the maximum implementation share of the optimal fertilization management scheme on the Isle of Dordrecht. Therefore, I compared the optimal results from each scenario with the maximum available recycling fertilizer available from the surroundings introduced in Table 5. Table 13 depicts the results of this evaluation.

Table 13: Maximum implementation of the optimal fertilization management

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Struvite	15%	29%	29%	73%
Bokashi	126%	98%	100%	160%
Hygenized sludge	55%	93%	92%	118%
Maximum implementation	**79%**	**100%**	**100%**	**62%**

Concluding it is to say that Scenarios 2 and 3 stays below the limits of maximum available recycling fertilizer and thus are applicable for the entire agricultural production (1750 ha) on the Isle of Dordrecht. Scenario 1 however exceeds the maximum average application of bokashi by 2.6 t/ha and period. Resulting in a maximum implementation of 79% corresponding to 1387 ha. Likewise, scenario 4 exceeds the max. application of bokashi and hygenized sludge by 6 and 2.3 t/ha and period indicating a maximal implementation of 62% (1091 ha) on the Isle of Dordrecht.

5. Discussion

Limiting the dependency on imported resources and commodities such as gas, oil, fodder and fertilizer is inevitable against the background of diminishing natural resources. This issue is accelerated by the current conflicts and geopolitical tensions. Following this, the aim to close the nutrient cycle between end consumers – especially in urban nutrient hotspots – and agricultural production and thus reduce imports is a pressing challenge to overcome. Adding to this my study provides insights into the field of the optimal implementation of recycling fertilizers in the nutrient management of an agricultural enterprise under agronomic considerations like nutrient availability and related uncertainty.

Substitution rates for mineral fertilizer

The highest substitution rate from mineral to recycling fertilizer was achieved in scenario 1 with 64% for nitrogen and 100% for phosphorus. The share of nitrogen stemming from the recycling fertilizer rate drops to 61% after introducing uncertainty to the model. It further diminishes when considering slurry as a not-recycling fertilizer to 43%. The phosphorus demand could be supplied to 100% from recycling sources in all scenarios (excluding baseline). Overall phosphorus shows a higher recycling potential than nitrogen across all scenarios with the chosen recycling concept.

This is mainly to be explained by the implementation of Struvite. Struvite shows the highest competitiveness compared to conventional mineral fertilizers like DAP due to its high nutrient content and availability. In combination with an organic fertilizer like slurry or hygenized sludge the whole demand for fast available phosphorus in potatoes, wheat and sugarbeet can be satisfied. This finding fits into the existing literature as nitrogen has a lower recycling potential compared to phosphorus. The recovery process of nitrogen out of human excreta is energy intensive (90 kJ/g N) and exceeds the energy demand for conventionally fixed nitrogen from the air (by the Haber-Bosch process, 53 kJ/g N) and is thus economically not yet viable (Maurer, Schwegler, & Larsen, 2003). However, new technologies are targeting more efficient recycling of nitrogen from source-separated urine as emphasized by Wald (2022).

By implementing recycling fertilizer (scenario 1), increasing the share of recycling fertilizer (scenario 2), and introducing uncertainty (scenario 3) the total amount of applied nutrients per period increases. This is to be explained by the on average lower availability of nutrients in the recycling fertilizer. Meaning that for the satisfaction of phosphorus and nitrogen demands from organic sources and recycling sources higher total nutrient applications are necessary. This leads to a decrease in nutrient use efficiency. The soil stock plays an important role in supplying nutrients, especially in the last periods when soil nutrient accumulation is high. Analogous to this are the findings of Klinglmair et al., 2017 in which the increase of recycling fertilizer over time was catalysed by higher soil nutrient content. However, with employing uncertainty in the model the utilization of the soil stock decreases as the nutrient release is fluctuating and less reliable.

Introducing the value of the organic matter in the model via implicit costs for mineral fertilizer shows no significant effect on the results (scenario 3). The monetary value I set as implicit costs did not influence the decision-making. Hence the value of organic matter needs to be considered higher by the individual decision maker to affect nutrient management significantly. However, the highest organic matter input was achieved in scenario 1 while the lowest was in scenario 4. This result undermines the importance of animal effluents such as slurry to deliver the organic matter to the soils and thus improving soil fertility.

With an increasing amount of nutrients supplied by recycling fertilizer, the total costs are rising. Resulting in the highest costs in scenario 1. This emphasizes the economic hurdle of implementing recycling and organic fertilizer into nutrient management to achieve high yields as highlighted by Hijbeek et al. (2018). According to the farm accountancy network (FADN) the total fertilization cost for a Dutch farmer in 2020 accounts for 181 €/ha/year. Hence the fertilization costs in my model ranging from 129 to 138 €/ha/year are realistic considering only nitrogen and phosphorus.

Maximum implementation

As the evaluation of the maximum implementation has shown only scenarios 2 and 3 could be applied to all agricultural production on the Isle of Dordrecht. This implies that 60 % of the nitrogen demand and 100% of the phosphorus demand can be satisfied from recycling sources. Considering slurry not as a recycling fertilizer in general or only for the Isle of Dordrecht the optimal fertilization management cannot fully be implemented in the case study area. This underlines the significance of animal effluents when aiming at a sustainable nutrient supply. This goes in line with the findings of Cordell and White (2013) which emphasize the importance of manure to achieve a sustainable phosphorus supply.

Graaff et al. (2011) emphasize that 36% of the Netherlands' phosphorus fertilizer consumption could potentially be recovered from sewage. My model replicates this figure quite accurate by indicating that 40% of the phosphorus demand was supplied by struvite and hygenized sludge (sewage) in scenario 2. Scenario 4 indicates a supply of 74.1% stemming from human excreta. This is to be explained as the Isle of Dordrecht is a comparatively small agricultural area next to a big urban area. Hence the amount of available sewage per ha is higher compared to the rest of the Netherlands.

Conclusively the share of recycling fertilizer on the Isle of Dordrecht in this model could only be increased by lowering the demand for nutrients which equates with lower yields. Further measures to decrease agricultural nutrient demand such as reducing storage and application losses, counteracting nutrient runoff and immobilization in the soil are auxiliary in this regard (Cordell & White, 2013).

Research and policy implications

The Dutch government set the aim to be the global leader in circular agriculture in 2030. Included in this aim is the recycling of residual flows from food production and consumption (Ministry of Agriculture, Nature and Food Quality of the Netherlands, 2019). To foster this ambition, it is important to ensure that the available resources appropriate for reuse in agriculture are made available. Specifically, this means ensuring the reuse of plastic-free household GFT waste, pollutant-free nutrients derived from human excreta and other sources. For this cheaper and cleaner nutrient recycling technologies are needed to achieve higher recycling ratios without contaminating soils. Further, more awareness of the value and acceptance of valuable resources (waste) in society and agriculture to accelerate the processes is needed.

Additionally, if manure application is further restricted by the Dutch government farmers need economically viable options to meet their plant's high nutrient demands and supply organic matter to their soils. To avoid the increase in mineral fertilization however other options need to be available at reasonable prices. Against this background, the utilization of hygenized sewage sludge should be considered in the Netherlands. Germany for instance enforces the P-recovery from sewage sludge for agricultural reuse by law in the coming years. Until now it was allowed to use sewage sludge for direct application in agricultural production. But from 2023 onwards, it will only be allowed to reuse sewage for direct application on agricultural land from wastewater treatment plants smaller than 50,000-person equivalents. While it is obligatory for WWTPs bigger than this to recover phosphorus (German Sewage Sludge Ordinance, 2017). A policy like this could counteract the substitution of manure for mineral fertilizer and follows the aim to achieve circular agriculture in the Netherlands.

Further research efforts must be made to investigate the nutrient recycling potential for nutrient hotspots (urban areas, industry etc.) in the Netherlands and optimize their implementation in regional agriculture. By doing so the overall Dutch mineral nutrient substitution potential can be calculated and optimally implemented in the current agricultural nutrient management and hence point the way towards a more sustainable nutrient supply. Implementing recent nutrient recycling technologies into a more comprehensive economic model (like a computable equilibrium model) presenting the Dutch economy and agriculture might deliver valuable insights into future nutrient supply scenarios.

Limitations of the study

As one of the drawbacks of linear programming models, the baseline scenario cannot reflect reality. Also, in my study, the baseline scenario differs from the actual situation and agricultural practices on the Isle of Dordrecht. Additionally, LP models tend to have corner solutions and jump from one to another instead of having a smooth alignment to the optimal solution. One approach to overcome these shortcomings is Positive Mathematical Programming (PMP). PMP calibrates the model in a way to better reproduce the observed reference values by adding a calibration constraint. The standard approach utilizes the dual values of the constraints to modify the objective function. A nonlinear model which has smoother responses to optimization is the result (Heckelei Thomas & Britz Wolfgang, 2005; Howitt, 1995). The jumpy behaviour in the optimization process is also to be found in my results indicated by the bimodality of the probability distribution of some variables.

Furthermore, the model is only focusing on the agricultural demand for main nutrients nitrogen and phosphorus while potassium and other micronutrients are left apart which would roundoff the resource allocation problem. Also, the chosen nutrient recycling technologies and fertilizer determine the outcome of the model. With a different nutrient recycling concept, the model will produce different results. In this context also, the assigned recycling fertilizer prices are based upon their nitrogen and phosphorus nutrient content solely while the real market prices may differ. Also, the value of other macro- and micronutrients is not accounted for. As another limitation, I have chosen a 9-period time horizon for my LP model. The planning horizon of a farming enterprise however might be shorter or longer. Further, the model produces unrealistic results in period 9 as there is no further nutrient demand expected in the next period. Lastly, the nutrient soil fluxes are highly complex and underly interrelating factors which are unforeseeable. Yet the soil stock depicted in my model is rather simple.

6. Conclusion

My research aimed at finding the optimal implementation scheme for recycling fertilizer without exceeding the cost constraint and satisfying the agricultural nutrient demand on the Isle of Dordrecht. Based on the multi-objective programming model supplemented by a Monte Carlo simulation to implement uncertainty recycling nitrogen and phosphorus were implemented to a high share in the research area. Also, with an increasing amount of recycling nutrients applied the total amount of nutrients is increasing indicating a reduction in nutrient use efficiency. To further increase the share of recycling fertilizer for nitrogen and phosphorus a reduction of yields to lower the nutrient demand seems inevitable. Especially when animal effluents like slurry are not considered as recycling fertilizer the supply of circular derived nutrients and organic matter is at risk. This gains in relevance as further legislative restrictions in this regard are to be expected. This research clearly illustrates the potential of utilizing recycling fertilizers in agriculture on the Isle of Dordrecht but also raises the question to which extent this implementation can be stretched across the Netherlands. My research contributed to the pressing questions regarding the future nutrient supply of modern European agriculture from a Dutch regional perspective and delivers an initial stage for further development on the Isle of Dordrecht. In times of conflicts and geopolitical tensions the need to ensure a sustainable nutrient supply for agricultural food production is substantial and needs further political and societal endeavours.

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Appendix

Appendix A: Input table of the multi-objective linear programming model

	Decision variables	Symbol	Unit
	Mineral fertilizer (DAP)	x_{DAP}	kg/ha/period
	Mineral fertilizer (urea)	x_{urea}	kg/ha/period
	Bokashi	x_b	kg/ha/period
	Hgyenized sludge	x_{hs}	kg/ha/period
	Struvite	x_s	kg/ha/period
	Slurry (cattle)	x_{sl}	kg/ha/period
	Soil stock (nitrogen)	s_n	kg/ha/period
	Soil stock (phosphorus)	s_p	kg/ha/period
	Total discounted costs (t)	c_{total}	EUR/ha/period
	Parameters		
Prices	Mineral fertilizer (DAP)	p_{DAP}	EUR/t
	Mineral fertilizer (urea)	p_{urea}	EUR/t
	Bokashi	p_b	EUR/t
	Hygenized sludge	p_{hs}	EUR/t
	Struvite	p_s	EUR/t
	Slurry (cattle)	p_{sl}	EUR/t
Nitrogen content	Mineral fertilizer (DAP)	c_{DAP}^n	%/DM
	Mineral fertilizer (urea)	c_{urea}^n	%/DM
	Bokashi	c_b^n	%/FM
	Hygenized sludge	c_{hs}^n	%/FM
	Struvite	c_s^n	%/DM
	Slurry (cattle)	c_{sl}^n	%/FM
Phosphorus content	Mineral fertilizer (DAP)	c_{DAP}^p	%/DM
	Mineral fertilizer (urea)	c_{urea}^p	%/DM
	Bokashi	c_b^p	%/FM
	Hygenized sludge	c_{hs}^p	%/FM
	Struvite	c_s^p	%/DM
	Slurry (cattle)	c_{sl}^p	%/FM
Nitrogen availability	Mineral fertilizer (DAP)	y_{DAP}^n	%/period
	Mineral fertilizer (urea)	y_{urea}^n	%/period
	Bokashi	y_b^n	%/period
	Hygenized sludge	y_{hs}^n	%/period
	Struvite	y_s^n	%/period
	Slurry (cattle)	y_{sl}^n	%/period
Phosphorus availability	Mineral fertilizer (DAP)	y_{DAP}^p	%/period
	Mineral fertilizer (urea)	y_{urea}^p	%/period
	Bokashi	y_b^p	%/period
	Hygenized sludge	y_{hs}^p	%/period
	Struvite	y_s^p	%/period
	Slurry (cattle)	y_{sl}^p	%/period

Soil stock	Nitrogen release from soil stock	r_n	%/period
	Nitrogen losses from soil stock	l_n	%/period
	Phosphorus release from soil stock	r_p	%/period
	Phosphorus losses from soil stock	l_p	%/period
Nutrient demand	Nitrogen demand max	d^n_{max}	kg/ha/period
	Phosphorus demand max	d^p_{max}	kg/ha/period
	Nitrogen demand min	d^n_{min}	kg/ha/period
	Phosphorus demand min	d^p_{min}	kg/ha/period
Others	Discount rate	d	%/period

Appendix B: Model input parameters

Table 14 Parameters for beta distribution

		Min	Baseline	Max	Alpha	Beta
Prices	Mineral (DAP)	0.2830	0.3600	0.5500	1.82	4.54
	Mineral (urea)	0.1900	0.2640	0.4420	1.90	4.57
	Bokashi	0.0000	0.0030	0.0030	1.80	0.18
	Hygenized sludge	0.0000	0.0020	0.0030	3.81	0.95
	Struvite	0.1790	0.2270	0.3470	1.79	4.52
	Slurry (cattle)	0.0000	0.0030	0.0030	3.81	0.95
Nitrogen content	Mineral (DAP)	0.1800	0.1800	0.1800	4.00	4.00
	Mineral (urea)	0.4600	0.4600	0.4600	4.00	4.00
	Bokashi	0.0018	0.0030	0.0100	0.60	3.20
	Hygenized sludge	0.0008	0.0020	0.0030	3.60	4.32
	Struvite	0.0500	0.0500	0.0500	1.80	0.18
	Slurry (cattle)	0.0019	0.0024	0.0038	1.44	4.31
Phosphorus content	Mineral (DAP)	0.4600	0.4600	0.4600	4.00	4.00
	Bokashi	0.00045	0.0010	0.0090	0.22	2.00
	Hygenized sludge	0.00075	0.0016	0.0020	4.65	2.19
	Struvite	0.2800	0.2800	0.2800	4.00	4.00
	Slurry (cattle)	0.0010	0.0017	0.0023	4.12	3.87
Nitrogen availability	Mineral (DAP)	1.0000	1.0000	1.0000	4.00	4.00
	Mineral (urea)	1.0000	1.0000	1.0000	4.00	4.00
	Bokashi	0.1900	0.2000	0.2100	4.00	4.00
	Hygenized sludge	0.1800	0.3000	0.4140	4.10	3.89
	Struvite	1.0000	1.0000	1.0000	4.00	4.00
	Slurry (cattle)	0.3000	0.5000	0.6900	4.10	3.89
Phosphorus availability	Mineral (DAP)	1.0000	1.0000	1.0000	4.00	4.00
	Bokashi	0.2000	0.2000	0.2100	4.00	4.00
	Hygenized sludge	0.4000	0.6000	0.8300	4.10	3.89
	Struvite	1.0000	1.0000	1.0000	4.00	4.00
	Slurry (cattle)	0.4600	0.7.000	0.9400	4.00	4.00
Soil stock	N-release rate	0.8000	0.9000	1.0000	4.00	4.00
	N-losses	0.0500	0.0800	0.1000	4.58	3.06
	P-release rate	0.3000	0.4000	0.5000	4.00	4.00
	P-losses	0.0300	0.0450	0.0600	4.00	4.00
	Implicit costs	0.0090	0.0150	0.0370	0.99	3.86

Appendix C: Calculation of implicit cost

I approximated the value of the organic matter in the organic fertilizer and thus the implicit cost of using mineral fertilizer to supply 1 kg of nitrogen by using the following approach:

- What is the average nitrogen content in the organic fertilizer apparent in the model?
    - 0.24%
- How high is the organic matter content in the apparent organic fertilizer?
    - 5.75%
- How much organic fertilizer is needed to supply 1 kg N?
    - 411kg
- How much organic matter is related to this?
    - 24kg

I used the estimated monetary value of 1% soil organic matter content from the literature. According to Sparling et al. (2006) 1 % of organic matter is worth 14 to 55€/ha/year. How much kg organic matter is related to 1% soil organic matter content? Assuming topsoil of 0.25 meters with a density of 1.4t/m^3 1% of organic matter equals 35 t/ha.

$$10{,}000m^2 \times 0.25\ m\ \times 1.4\frac{t}{m^3} \times 1\% = 35\frac{t}{ha} \qquad \text{Eq. (15)}$$

Based on these figures I calculated the value of organic matter corresponding to supplying one 1kg nitrogen from organic fertilizers.

Appendix D: Fertilization costs in scenario 2

Table 15: Descriptive statistics of the fertilization costs in scenario 2

	P1	P2	P3	P4	P5	P6	P7	P8	P9
Average	203.63	172.16	119.81	182.78	157.20	109.52	168.28	84.51	20.84
Median	203.64	172.31	120.48	183.73	156.83	108.12	167.70	85.10	17.54
Standardeviation	25.00	23.28	21.20	27.20	31.11	29.71	33.38	19.21	12.46
Variance	624.79	541.95	449.25	739.98	967.97	882.68	1114.22	369.00	155.35
Minimum	111.53	96.29	38.22	78.57	64.91	20.84	55.14	35.32	0.00
Maximum	290.41	250.61	185.04	267.31	255.39	189.85	267.31	155.83	80.37
Iteration	10000	10000	10000	10000	10000	10000	10000	10000	10000
CI (95%)	0.49	0.46	0.42	0.53	0.61	0.58	0.65	0.38	0.24
Upper limit	204.1	172.6	120.2	183.3	157.8	110.1	168.93	84.9	21.08
Lower limit	203.1	171.7	119.4	182.2	156.6	108.9	167.63	84.1	20.59

Appendix E: Statistical analysis of recycling fertilizer use in scenario 2 and 3

Table 16: Two tailed t-test to compare the recycling fertilizer used in scenario 2 and 3

		Average	Variance	P-value
P1	Scenario 2	34.94%	0.00149	0.76
	Scenario 3	34.93%	0.00152	
P2	Scenario 2	32.62%	0.0013	0.87
	Scenario 3	32.61%	0.0013	
P3	Scenario 2	67.63%	0.0021	0.93
	Scenario 3	67.62%	0.0021	
P4	Scenario 2	54.48%	0.0014	0.87
	Scenario 3	54.47%	0.0014	
P5	Scenario 2	56.97%	0.0061	0.97
	Scenario 3	56.97%	0.0060	
P6	Scenario 2	94.15%	0.0048	0.48
	Scenario 3	94.08%	0.0048	
P7	Scenario 2	74.35%	0.0086	0.74
	Scenario 3	74.39%	0.0085	
P8	Scenario 2	43.28%	0.0385	0.54
	Scenario 3	43.45%	0.0384	
P9	Scenario 2	90.56%	0.0494	0.59
	Scenario 3	90.73%	0.0481	

Appendix F: Nutrient supply by fertilizer in scenario 4

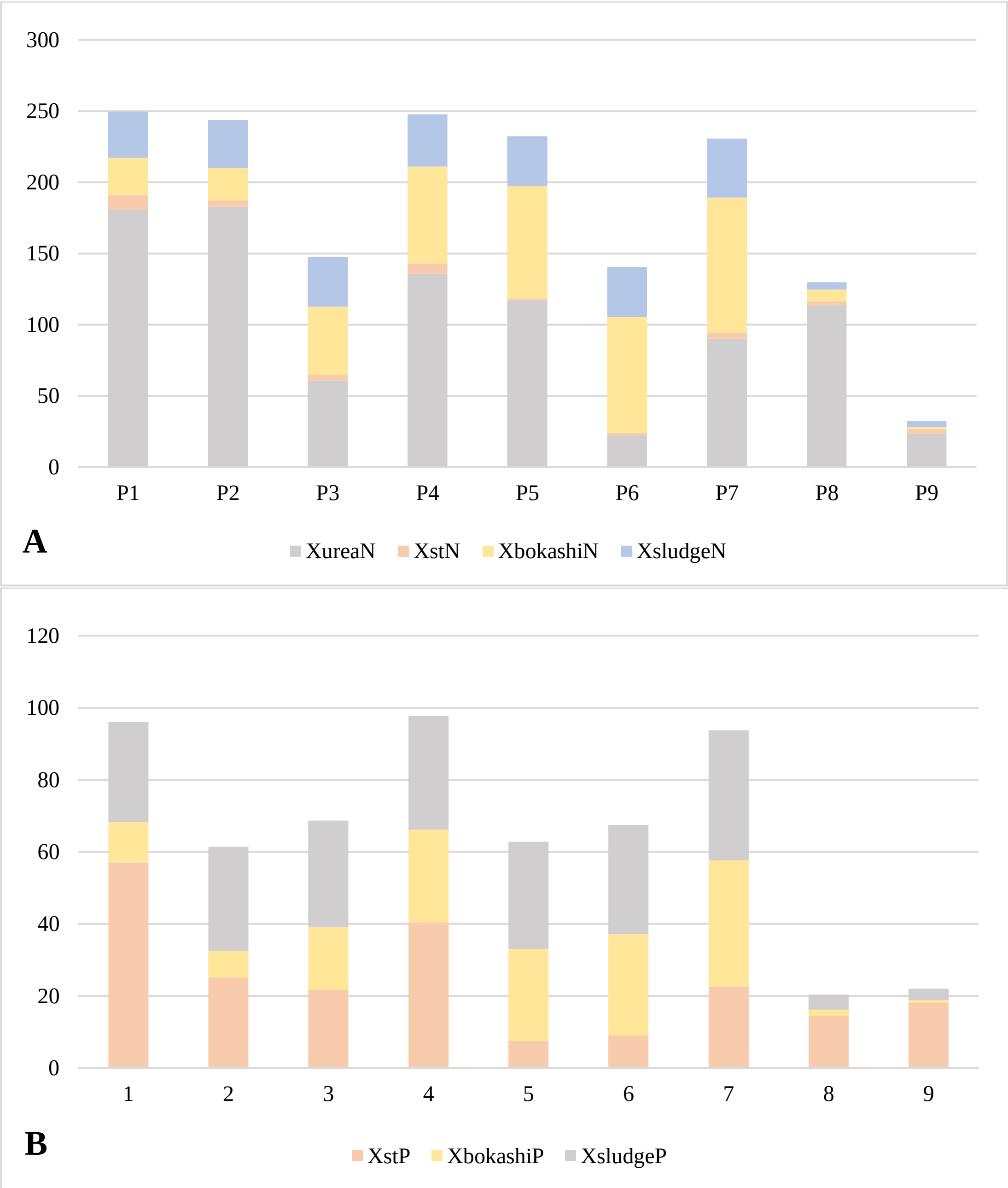

Figure 16: Nitrogen (A) and phosphorus (B) supply by fertilizer in scenario 4

Appendix G: Nutrient losses and release rates

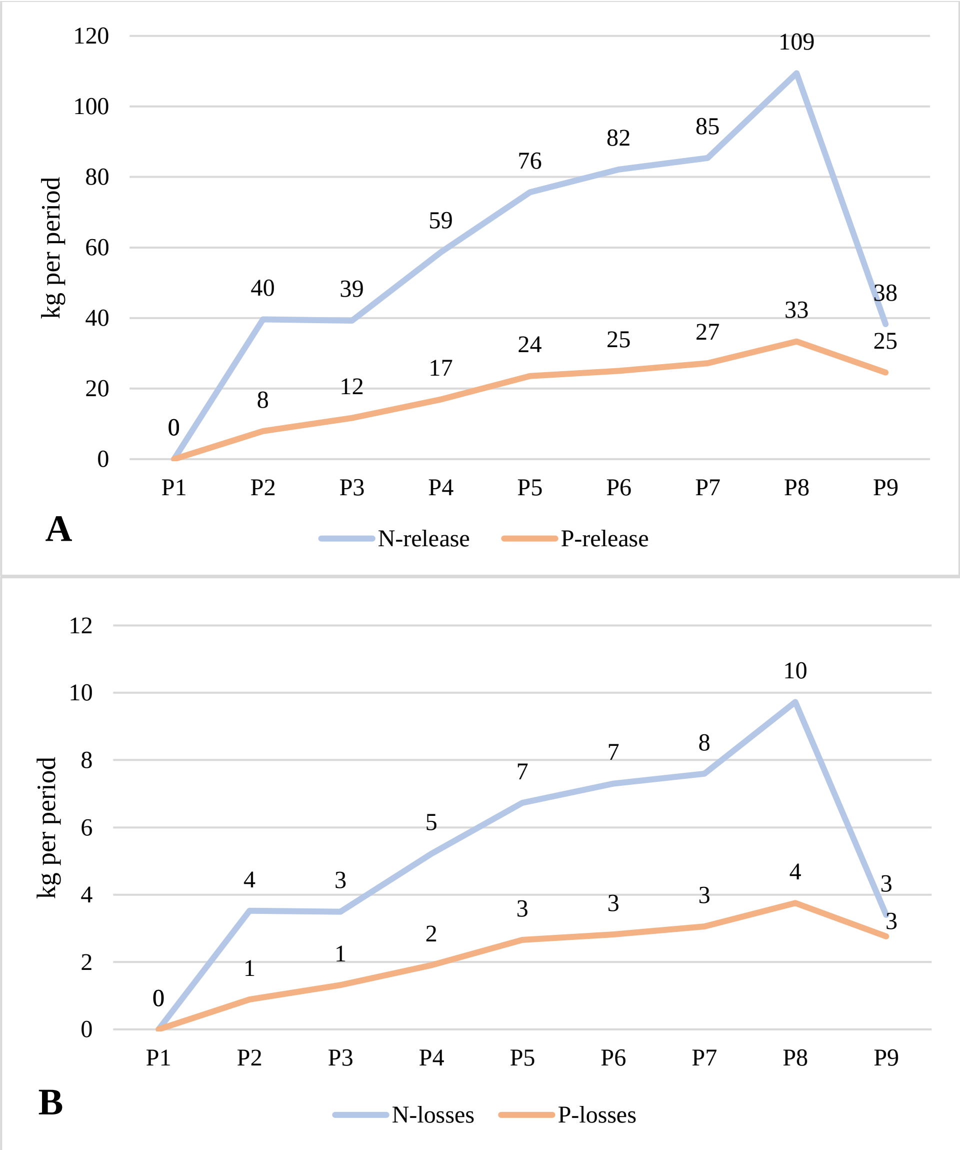

Figure 17: Nitrogen (A) and phosphorus (B) losses and release in kg/period

Appendix H: Results baseline scenario

Table 17: Full results baseline scenario in kg per period

	P1	P2	P3	P4	P5	P6	P7	P8	P9
xmin	84	16	49	63	0	37	57	0	35
Xurea	333	353	128	268	314	132	271	314	133
Xst	0	0	0	0	0	0	0	0	0
Xb	0	0	0	0	0	0	0	0	0
Xhs	0	0	0	0	0	0	0	0	0
Xma	31250	30625	18750	31250	30625	18750	31250	30625	18750
XminN	15	3	9	11	0	7	10	0	6
XureaN	153	162	59	123	144	61	124	144	61
XstN	0	0	0	0	0	0	0	0	0
XbokashiN	0	0	0	0	0	0	0	0	0
XsludgeN	0	0	0	0	0	0	0	0	0
XslurryN	75	74	45	75	74	45	75	74	45
XminP	39	8	22	29	0	17	26	0	16
XstP	0	0	0	0	0	0	0	0	0
XbokashiP	0	0	0	0	0	0	0	0	0
XsludgeP	0	0	0	0	0	0	0	0	0
XslurryP	53	52	32	53	52	32	53	52	32
TotalCosts (€)	198	177	99	173	161	96	172	161	96
TotalCostsdis (€)	198	170	92	154	138	79	136	122	70
Psoil	0	16	24	23	29	32	27	31	33
Nsoil	0	38	38	23	38	38	23	38	38
Xnonrecy	418	369	177	331	314	169	328	314	168

Appendix I: Results scenario 1

Table 18: Full results scenario 1 in kg per period

	P1	P2	P3	P4	P5	P6	P7	P8	P9
xmin	0	0	0	0	0	0	0	0	0
Xurea	347	352	101	242	224	11	106	155	0
Xst	121	10	0	0	0	0	0	0	32
Xb	0	0	7270	4920	34191	32193	35000	0	0
Xhs	5159	4960	19898	26818	0	0	7644	0	0
Xma	31250	30625	18750	31250	15031	18750	31250	30625	0
XminN	0	0	0	0	0	0	0	0	0
XureaN	160	162	47	111	103	5	49	71	0
XstN	6	0	0	0	0	0	0	0	2
XbokashiN	0	0	23	15	106	100	109	0	0
XsludgeN	9	9	36	48	0	0	14	0	0
XslurryN	75	74	45	75	36	45	75	74	0
XminP	0	0	0	0	0	0	0	0	0
XstP	34	3	0	0	0	0	0	0	9
XbokashiP	0	0	9	6	44	42	46	0	0
XsludgeP	8	8	32	43	0	0	12	0	0
XslurryP	53	52	32	53	26	32	53	52	0
U	1362	1362	1362	1362	1362	1362	1362	1362	1362
TotalCosts (€)	210	184	137	214	189	137	217	119	7
TotalCostsdis (€)	210	177	126	191	161	112	172	91	5
Psoil	0	19	29	46	64	79	87	105	74
Nsoil	0	44	44	66	85	105	104	136	39
Xnonrecy	347	352	101	242	224	11	106	155	0

Appendix J: Results scenario 2

Table 19: Full results scenario 2 in kg per period

	P1	P2	P3	P4	P5	P6	P7	P8	P9
XminN	0	0	0	0	0	0	0	0	0
XureaN	163	165	48	114	99	8	63	84	4
XstN	7	2	1	2	0	0	1	0	2
XbokashiN	6	6	27	27	64	66	66	13	1
XsludgeN	12	11	35	42	20	34	50	6	3
XslurryN	62	61	38	65	50	34	64	54	15
XminP	0	0	0	0	0	0	0	0	0
XstP	38	8	8	12	1	3	4	2	12
XbokashiP	3	2	8	9	17	19	20	2	1
XsludgeP	10	9	29	35	14	27	41	4	2
XslurryP	44	43	27	46	35	24	45	37	11
TotalCostsdis (€)	204	172	120	183	157	110	168	85	21
Psoil	0	20	29	42	59	63	68	83	61
Nsoil	0	44	44	65	84	91	95	122	43
Xmin	0	0	0	0	0	0	0	0	0
Xurea	354	359	104	247	215	17	136	184	9
Xst	136	30	28	42	3	10	15	7	42
Xb	1779	1825	8506	8149	21802	22272	21362	2479	309
Xhs	6346	5714	18149	22110	9452	17101	25753	2788	1341
Xma	26028	25488	15661	27277	20747	13988	26841	22082	6399
Xnonrecy	354	359	104	247	215	17	136	184	9

Appendix K: Results scenario 3

Table 20: Full results scenario 3 in kg per period

	P1	P2	P3	P4	P5	P6	P7	P8	P9
XminN	0	0	0	0	0	0	0	0	0
XureaN	163	165	48	114	99	8	62	84	4
XstN	7	2	1	2	0	1	1	0	2
XbokashiN	6	6	27	27	64	67	68	13	1
XsludgeN	12	11	34	42	19	32	48	6	3
XslurryN	62	61	37	65	50	34	64	53	15
XminP	0	0	0	0	0	0	0	0	0
XstP	38	8	8	12	1	3	4	2	12
XbokashiP	3	2	9	9	18	20	20	2	1
XsludgeP	11	9	29	36	14	26	40	5	2
XslurryP	44	43	27	46	35	24	45	37	11
TotalCostsdis (€)	206	175	121	185	158	110	169	86	21
Psoil	0	20	29	43	59	63	68	84	62
Nsoil	0	44	44	65	84	91	95	122	43
ImplicitCosts (€)	2.5	2.5	0.7	1.7	1.5	0.1	0.9	1.3	0.1
Xmin	0	0	0	0	0	0	0	0	0
Xurea	354	359	104	247	216	17	136	183	9
Xst	135	30	28	42	3	10	14	6	41
Xb	1763	1873	8686	8277	22069	22661	21803	2544	269
Xhs	6661	5861	18000	22166	9202	16575	25189	2863	1380
Xma	25816	25328	15599	27160	20596	13931	26874	22023	6354
Xnonrecy	354	359	104	247	216	17	136	183	9

Appendix L: Results scenario 4

Table 21: Full results scenario 4 in kg per period

	P1	P2	P3	P4	P5	P6	P7	P8	P9
XminN	0	0	0	0	0	0	0	0	0
XureaN	181	183	61	136	117	22	90	114	23
XstN	10	4	4	7	1	2	4	3	3
XbokashiN	26	23	48	68	79	81	95	8	2
XsludgeN	32	34	35	37	35	35	41	5	4
XslurryN	0	0	0	0	0	0	0	0	0
XminP	0	0	0	0	0	0	0	0	0
XstP	57	25	22	40	8	9	23	14	18
XbokashiP	11	7	17	26	26	28	35	2	1
XsludgeP	28	29	30	32	30	30	36	4	3
XslurryP	0	0	0	0	0	0	0	0	0
TotalCostsdis (€)	209	175	124	192	158	110	161	64	23
Psoil	0	20	29	42	56	64	70	81	48
Nsoil	0	44	43	64	81	89	92	107	13
ImplicitCosts (€)	3	3	1	2	2	0	1	2	0
Xmin	0	0	0	0	0	0	0	0	0
Xurea	393	397	132	295	254	49	196	247	51
Xst	204	90	78	145	27	33	80	51	64
Xb	8476	7233	16446	23696	26894	27766	31709	1685	513
Xhs	17221	17938	18510	19673	18663	19011	22544	2615	1964
Xma	0	0	0	0	0	0	0	0	0
Xnonrecy	393	397	132	295	254	49	196	247	51