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The Implications of a Reduction in Nitrogen Imports Embedded in Feed for Dutch Dairy Cattle

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Summary

Nitrogen is one of the most important nutrients in agriculture as it is the main limiting nutrient in crop growth. At the same time, however, due to the intensive production system, there is a large Nitrogen surplus leading to environmental impacts. In the Netherlands, the Nitrogen losses have led to the so-called Nitrogen crisis which threatens the coexistence of Dutch nature areas. Since the agricultural sector is the largest contributor to Nitrogen deposition in the Netherlands, a large part of the policies related to Nitrogen emissions is focused on this sector. Especially, dairy farming is subject to heated debates about how to reduce the Nitrogen emissions. Circular Agriculture, the economic use of raw materials with as few imports and exports from outside the system, is currently seen as part of the solution for the Nitrogen crisis. However, although Circular Agriculture shapes the future for dairy farming, what this future is going to look like and on what scale circularity should take place is unsettled.

Circular Agriculture can take place on global scale, European scale, and national scale. This thesis assessed the implications of these scopes of circularity by eliminated N import through feed in the Dutch dairy farming sector. N embedded in feed is the largest import of N into the system and the elimination of these imports changes the environmental N flows. Three counterfactual scenarios were written and simulated to assess the implications of a reduction in Nitrogen imports embedded in feed for cattle stock, dairy production, and N emissions in 2018. In the reference scenario, the conventional situation in the Dutch dairy sector in 2018 was simulated. In the second scenario, Nitrogen imports embedded in feed imports from outside Europe were eliminated. And in the third scenario, Nitrogen imports embedded in feed imports from outside the Netherlands were eliminated. The situation in 2018 was simulated using public data sources. By assessing the implications of these scenario, this thesis aimed to inform policymakers whether the desirable Nitrogen emission targets can be achieved through these measures.

In the reference scenario, the Netherlands imports large quantities of Nitrogen embedded in feed products. The large import of Nitrogen results in Nitrogen losses to the environment, mainly through manure excretion and storage, and fertilizer application. The decrease in imports of Nitrogen result in a smaller cattle stock, a decrease in milk production and a reduction in Nitrogen emissions. The three scenarios do not directly affect Dutch consumption of dairy products as with Dutch feed production only the Dutch dairy sector still produces sufficient dairy from local demand. The scenarios, however, do affect the social-economic situation of dairy farmers, and the feed exporting and dairy importing countries as the production and exports of the sector reduce significantly. The reduction in cattle stock and Nitrogen emissions contribute to Dutch policies and policy advise, related to the protection of biodiversity and water quality, the decrease in protein content of feed, the increase in self-sufficiency of the European Union concerning protein crops and the decrease in Nitrogen emissions in agriculture. However, the reduction in N emissions in the different scenarios compared to the reference scenario is in itself not enough to reach the target of 26% reduction in N emissions by 2030.

The reduction in feed imports could contribute to the Dutch agricultural system reaching its environmental sustainability targets, but it requires careful management to avoid negatively impacting social sustainability factors among producers and stakeholders in trading countries.

Preface and Acknowledgements

Before you lies my thesis “The implications of a reduction in Nitrogen imports through feed for the Dutch dairy sector”, a quantitative study for the master *Sustainable Development: Environmental Change and Ecosystems* of Utrecht University.

The thesis was undertaken and formulated together with my supervisor, Brian Dermody. After considering many different research subjects, a mutual interest in the current societal, environmental, and economic challenges within the agricultural sector shaped the research as it lies before you. The extensive research into the Dutch dairy farming sector that emerged has allowed me to answer the research question that was identified.

I would like to thank my supervisor for his engagement and extensive guidance. Brian has challenged and supported me during the process to achieve the result as it is. I also wish to thank W. van Straalen, W. Thielen, J. Roefs, G. Kaptijn, R. Goselink, S. Broekhuis for answering my emails and providing me with new insights. I would especially like to thank F. Gort for offering data on compound feed.

My friends I would like to thank for their motivation and inspiration, and for checking my work. My family and partner deserve a particular note of thanks: your motivation has kept me going as well as your wise words and kind counsel.

I hope you enjoy reading my MSc thesis.

Lotte Huiberts

Arnhem, August 3, 2021

List of Abbreviations

BNF	Biological Nitrogen Fixation
CA	Circular Agriculture
CBS	The Dutch National Statistical Office
DCC	Dairy cattle category
DON	Dissolved Organic Nitrogen
DS	Dry Matter
DVE	Gut digestible protein
EU	European Union
EUROSTAT	Statistical database of the European Union
FAO	Food and Agricultural Organisation of the United Nations
FAOSTAT	Statistical database of the Food and Agricultural Organisation
Ha	Hectare
Kg	Kilogram
MC	Milk cows
Ministry of LNV	Ministry of Agriculture, Nature and Food Quality
N	Nitrogen
N_2	Dinitrogen
N_r	Reactive Nitrogenous Compounds
NH_3	Ammonia
NH_4^+	Ammonium
N_2O	Nitrous Oxide
NOx	Nitrogen Oxides
NO_3^-	Nitrate
NO_2^-	Nitrogen Dioxide
OM	Organic Matter
RE	Crude Protein
RVO	Dutch National Office for Entrepreneurs
StatLine	Statistical Database of the Dutch National Statistical Office
VEM	Energy need per unit milk
YS<1	Young stock younger than 1 year
YS>1	Young stock older than 1 year

1. Introduction

1.1 Worldwide Agricultural Trends

In the last decades, there is a growing tension between agricultural production and environmental impacts (Runhaar, 2017; Vrolijk et al., 2020). Improved crop varieties, pesticide use, and the application of synthetic fertilizers have increased agricultural production (Lassaletta, Billen, Grizzetti, Anglade, et al., 2014) which made essential developments for human livelihood security and nutrition possible (Kanter et al., 2018). At the same time, however, agricultural intensification increased the use of inputs in agriculture which is associated with adverse environmental effects driving the environment beyond the planetary boundaries (Rockström et al., 2009; Therond et al., 2017). Decreased biodiversity and soil quality, increased eutrophication, acidification, and chemical pollution, and the alteration of surface and groundwater resources are examples of how agricultural food production is unfavourably affecting the environment (de Boer & van Ittersum, 2018; FAO, 2017; Lassaletta, Billen, Grizzetti, Anglade, et al., 2014). There is an increasing consensus among scientists of the importance of the agricultural sector in tackling many problems of our century; climate change, biodiversity loss, soil degradation, and an increasing world population (Adams et al., 1992; Singh & Singh, 2017).

1.2 Nitrogen in Agriculture

One of the main nutrients associated with the intensification of agriculture the last decades is Nitrogen (N) (Bodirsky et al., 2014; Zhang et al., 2015). N is one of the most important nutrients as it is a key component of amino acids, the building blocks of protein and nucleic acids. Plants and animals use N for metabolic processes, growth, and the production of milk, meat, eggs, or crops (W. de Vries & Schulte-Uebbing, 2019; FAO, 2017; Meeusen et al., 2003). Although the atmosphere consists for 78% of molecular dinitrogen (N_2), N is only limited available to plants or animals since N_2 is nonreactive. Only through N fixation, the nonreactive N_2 from the atmosphere can be converted into reactive nitrogenous compounds (N_r) and become available for plant uptake (Fowler et al., 2013). N_r includes all active N compounds in the Earth's atmosphere and biosphere (Galloway et al., 2003). The main process through which N becomes available for plant uptake is Biological N Fixation (BNF). BNF is the process in which micro-organisms, especially bacteria, convert the gaseous N from the atmosphere into N_r (*Biological Nitrogen Fixation-Symbiotic and Asymbiotic*, n.d.; Fowler et al., 2013). When plants die, or are eaten and excreted by animals, N becomes available to plants again or is converted back into the gaseous N_2 by micro-organisms. This cycling of N through the atmosphere and the terrestrial ecosystem (See Figure 1) is part of the biogeochemical movement of N of the Earth called the global N cycle. Besides natural N fixation by BNF and lightning, humans influence the global N cycle by the production of N_r (Fowler et al., 2013). In food production systems, the use of chemical fertilizers produced through industrial N fixation largely influences the natural N cycle (Fowler et al., 2013). Furthermore, the global character of the current food system, in which N is imported through feed and N is exported through animal products, causes an accumulation or shortage of N in different areas in the world (Lassaletta, Billen, Grizzetti, Garnier, et al., 2014).

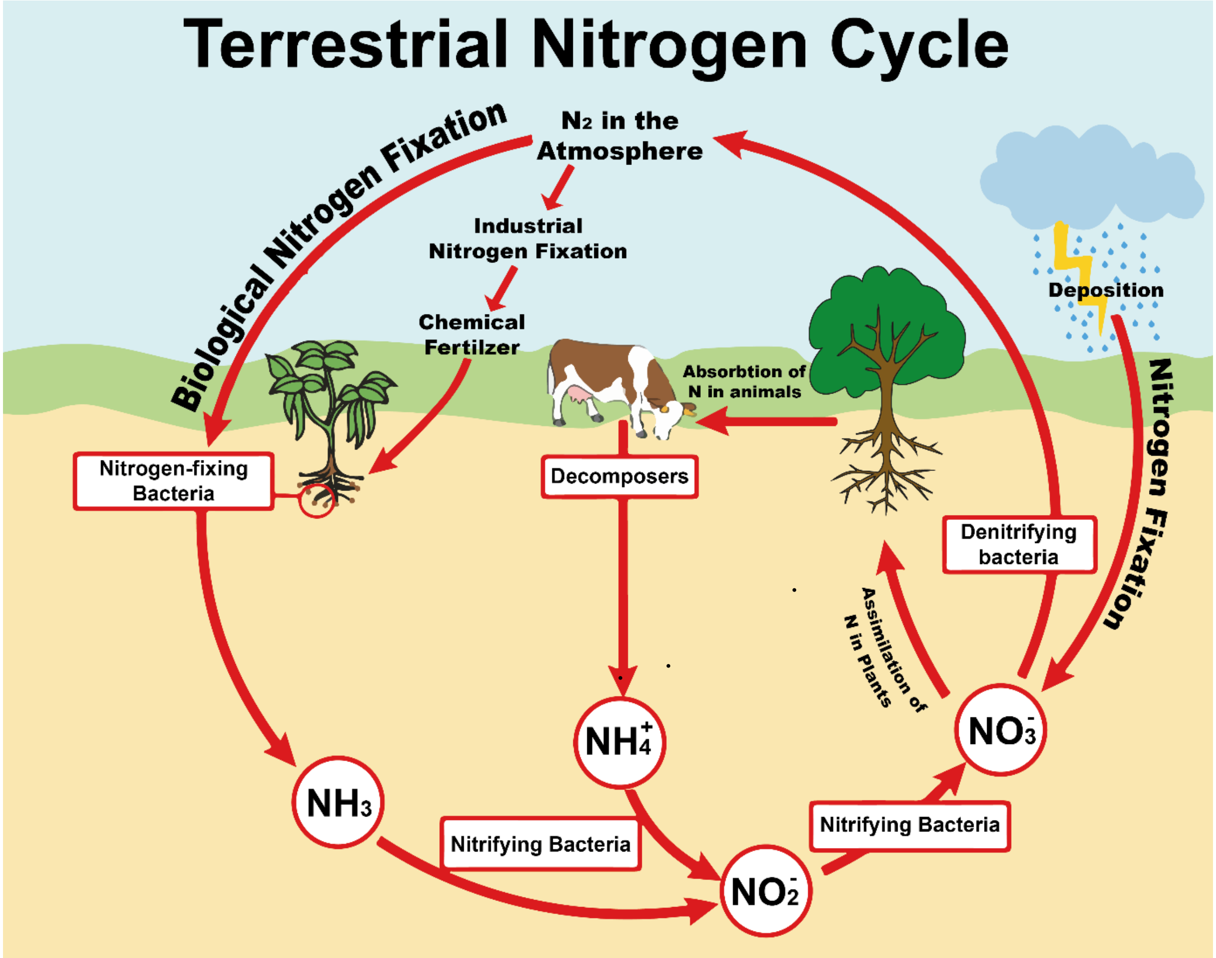

Figure 1. *Schematic representation of the terrestrial Nitrogen (N) cycle. The squared text boxes represent the micro-organisms which convert the N into different forms. The round text boxes represent the reactive N (N_r) in the soil. There are three processes through which the nonreactive dinitrogen (N_2) from the atmosphere can become available for plant uptake: Biological N Fixation (BNF), industrial N fixation, and deposition. Herbivores acquire the N from plants through grazing. Through the decomposition of animal excretion, plant residues and animal remain by micro-organisms called decomposers, the N_r can become available for plant uptake again. N_r can also be converted back to N_2 in the atmosphere. This Figure is based on Nitrogen Cycle (2021).*

Within the Netherlands, the anthropogenic N fixation, and the globalised character of the agricultural production system, have caused agricultural systems to be much larger than based on national produce only (Dolman et al., 2019). High input of N into the agricultural system in the form of N fertilisers and imported animal feed allow an increased productivity of arable and livestock farming, but also causes an accumulation of N_r in the soil (soil surplus) and atmosphere (emissions). In the Netherlands, this accumulation in the agricultural sector accounted for 330-million-kilogram (Kg) N in 2018 (Compendium voor de Leefomgeving, 2020). Such losses of N lead to the so-called N cascade phenomenon. This phenomenon refers to the circulation of anthropogenic N causing multiple side-effects (Foskolos & Moorby, 2018), such as, ammonia (NH_3) emissions contributing to climate change and decreasing plant species diversity through deposition on terrestrial ecosystems, nitrate (NO_3^-) causing decreased water quality, nitrous oxide (N_2O) emissions reinforcing climate change, and N runoff leading to eutrophication of surface waters (W. de Vries et al., 2021). Balancing N in agriculture is an important but demanding activity; too little N means lower productivity, poor human health, and soil degradation, but too much N leads to environmental pollution (Zhang et al., 2015).

1.3 Sustainable Transition

Scientists, society, and politicians have increasingly expressed the need for a sustainable transition in the Dutch agricultural production system, in which N losses and waste is minimised (el Bilali & Allahyari, 2018; Runhaar, 2017). As a consequence, several policies have been implemented to tackle the excessive N in the Netherlands at national, European, and international level. On the international level, the Paris Agreements (2015) target a reduction in greenhouse gases. On the European Union (EU) level, the Nitrate Directive (1991), the Habitats Directive (1992), the Water Framework Directive (2000) and the National Emission Ceilings Directive (2001) aim to reduce N emissions and pollution (W. de Vries et al., 2021). On the national level, the Nitrate Directive, Climate Agreement and Framework Directive Water intent to reduce N losses and waste (Remkes et al., 2020). These directives have contributed to manure and fertilizer legislation, restricting their use in Dutch agriculture. Between 1990 and 2018, the N inputs have decreased by 35%, and the N surplus decreased by 29% in the Netherlands while yields continued to increase (W. de Vries et al., 2021; Fuchs, 2020). Nevertheless, these policies and resulting reduction in N losses could not prevent a crisis and the need for a new vision on agricultural production in the Netherlands.

In 2019, the excessive N losses to the environment in the Netherlands, has led to the so-called 'Nitrogen crises. N pollution threatens 118 of the 162 Dutch nature reserves (Stokstad, 2019), and due to unfounded policy assumption on future decreases in N deposition, the court ruled that permits of around 18.000 construction- and infrastructure projects were inadmissible (Remkes et al., 2019). The Advisory Board on Nitrogen Problems advises a reduction of N emissions of 50% by 2030 to protect the Dutch nature areas (Remkes et al., 2020). Since agriculture is the largest source of N deposition in the Netherlands, accounting for 46% in 2018, the advice of the Advisory Board of Nitrogen Problems has large implications for the agricultural sector. Especially the dairy sector, which is responsible for 55% of the N emissions of the agricultural sector (Remkes et al., 2020), is located on a crossroad.

The reduction of N losses can be achieved by restoring the balance of minerals used in agriculture (Remkes et al., 2020). Increased mineral balancing, coincides with the visions for the future of agriculture of the Netherlands, Circular Agriculture (CA), and the EU, Farm to Fork Strategy, which aim for a more efficient use of nutrients (European Commission, 2020; Ministerie van LNV, 2018). In 2018, the Ministry of Agriculture, Nature and Food Quality (Ministry of LNV) presented a vision for the transition of the Dutch agricultural system to CA (Ministerie van LNV, 2018; Vrolijk et al., 2020). The concept CA is broadly defined as an agricultural system in which imports, and exports are minimised by creating closed loops in which imports are reduced and valuable products are recycled into the system (Grumbine et al., 2021). CA is seen as one of the solutions to solve the Dutch N crisis (Ministerie van LNV, 2019b; Remkes et al., 2019; Sikkema, 2019; Vink et al., 2021; Vrolijk et al., 2020), however, it is also criticised for being unclear with an undefined scope (Berkum, 2018; Dolman et al., 2019; Vrolijk et al., 2020).

Dolman et al. (2019) identified three spatial scales which can be applied to study the closing of the N cycle in CA: the global scale, the European scale, and the national scale. This thesis assesses the implications of these scopes of circularity by eliminated N import through feed in the Dutch dairy farming sector. N embedded in feed is the largest import of N into the system and the elimination of these imports changes the environmental N flows. By researching the implications of these changes, it is studied whether the elimination of feed imports can reach the Dutch N emission reduction targets. The role of the dairy sector in these issues is widely acknowledged as the sector must meet sectoral, national, European, and international policy objectives for reducing N emissions (M. de Vries et al., 2018). The implications of the different scopes of circularity are studied for the Dutch dairy farming system since this sector has a high economic and social value (M. de Vries et al., 2018; Remkes et al., 2019), but at the same time has the largest N emissions of all Dutch agricultural sectors (Remkes et al., 2019).

1.4 Scientific Relevance

The vision of the Ministry of LNV for CA shapes the future of dairy farming in the Netherlands. However, what this future is going to look like and on what scale CA should take place is unsettled (Ploegmakers et al., 2020). As a result, the implications of different scopes of circularity for the dairy sector, the society and the environment are, is largely unknown (Berkum, 2018; Dolman et al., 2019; Vrolijk et al., 2020). Due to a lack of systemic analysis of the N flows in the Dutch dairy sector and the scope at which circularity should take place, it is unclear where the options for interventions in the system are. Existing research qualitatively and quantitatively attempts to assess the implications of CA for the agricultural sector. Previous research on N and CA has either focused on the entire agricultural sector (Bremmer et al., 2021; Dolman et al., 2019), on system components, such as biodiversity (Dijkshoorn-Dekker & Kortstee, 2020), or on farm-level case studies and pioneers (Mollenhorst & de Haan, 2021; Pijlman, 2020; van Rotterdam et al., 2021). Research on the implications of CA for the Dutch dairy sector specifically is limited. Silvis et al. (2021) and Terluin et al. (2013) do assess the implications of eliminating feed imports on different spatial scales on milk cattle stock and milk production. Yet even though this sector has the largest N emissions of all agricultural branches (Bergevoet et al., 2019), there is no research that assesses the implications of the different scopes of circularity for the N emissions of the Dutch dairy sector specifically.

1.3 Societal Relevance

The transition of the dairy sector to CA and the measures proposed to tackle the N crisis can have large social implications. The Dutch dairy sector has an important added value for the Netherlands as the sector employs 49.000 full-time employees (NZO, 2019). Furthermore, dairy farming has the second largest gross production value of agriculture, responsible for 5,0 billion Euro (ZuivelNL, 2019a). The entire dairy sector has a production value of 7,5 billion Euro for the Netherlands, and accounts for 7% of the Dutch trade balance. The importance of trade for the dairy sector is underlined by the fact that in total 65% of the dairy produced is exported (ZuivelNL, 2019a, 2019b). Within the EU, the Netherlands is the fourth largest producer of milk after Germany, France, and the United Kingdom, with a share of 8,4% of total EU production in 2018 (*Production and Utilization of Milk on the Farm - Annual Data*, 2021). The per capita revenue of the dairy sector even ranks second place in the EU, far exceeding the top three producers in 2018 (ZuivelNL, 2019a).

Besides the economic value, the Dutch dairy sector also has an important social value. Grazing cattle has become part of the Dutch cultural landscape and traditional cultural heritage as a result of the long tradition of landbound cattle farming in the Netherlands (Hin et al., 2004; van den Pol-van Dasselaar et al., 2021). In addition, the consumption of dairy is seen as part of a healthy diet in the Netherlands. Although the Dutch government aims for a reduction in protein intake through its food consumption advise, it is not part of their recommendations to reduce the current daily intake of dairy (Gezondheidsraad, 2015; Peters et al., 2020). The consumption of cheese on sandwiches, as well as the *Edammer* and *Goudse* cheese, is even officially part of the Dutch natural immaterial heritage (Hin et al., 2004; *Immaterieel Erfgoed in Nederland*, 2021; van den Pol-van Dasselaar et al., 2021). Although the consumption of dairy is positively linked to health, the emissions of N of the sector can negatively affect human health. It is estimated that the health issues related to the N emissions from the dairy sector cost the society between 1 to 13 euro per 100 kg milk (Rougoor & van der Schans, 2017). Hence, the dairy sector has a high societal value as it can affect employment, income, trade, consumption, cultural heritage, and human health. Mapping out the current N flows and the changes of these flow due to decreased feed imports in the diary sector is thus of importance for society.

1.5 Research Objective

This thesis aims to contribute to closing the research gap by assessing the implications of three different counterfactual scenarios for the scope of CA in the Dutch dairy sector on cattle stock, milk production and N emissions in 2018. First, a system level quantification of N flows in the Dutch dairy farming system is made by a systemic analysis of the situation in 2018. Second, three scenarios are assessed: A) the reference scenario or conventional situation in the Dutch dairy sector in 2018, B) the elimination of feed imports from outside Europe, and C) the elimination of feed imports altogether. CA revolves around the economical use of raw materials with as few imports and exports from outside the system (Scholten et al., 2018). The largest import of N into the Dutch dairy farming system is through the import of feed. The elimination of feed changes the environmental N flows and impacts the cattle stock, dairy production, and N emissions. By assessing these implications, this thesis aims to inform policymakers about the consequences of the elimination of feed imports from the different scopes of circularity for the dairy farming sector and whether the desirable N emission targets can be achieved through these measures.

With the three scenarios, the changes of N in the Dutch dairy sector are explored by answering the following research question:

> *What are the implications on cattle stock, dairy production, and N emissions of a reduction in N embedded in imported feed in the Dutch dairy farming system?*

Chapter 2 discusses the historical developments of the Dutch dairy sector which have led to the vision for CA of the Ministry of LNV. The chapter also discusses the terrestrial N cycle in detail and explains the nutritional value of feed. The methodology to test the three scenarios, including a description of the scenarios, is described in *Chapter 3. Chapter 4* contains the results of the three different scenarios, and *Chapter 5* the discussion of these results. The main findings of this research are concluded in *Chapter 6.*

2. Background: Nitrogen Flows in the Dutch Dairy Sector

To understand the importance of N in agricultural production systems, and the negative environmental impacts resulting from it, it is important to understand the historical developments of agricultural in Europe. These historical developments are closely related to the comprehension of the N cycling in the terrestrial ecosystem. To appreciate the alteration of the N cycle by humans, it is necessary to first discuss the state of the N cycle prior to human alteration. Therefore, the first section starts with a brief discussion on the development of agriculture and the natural N cycling in terrestrial ecosystems. The second section proceeds with the historical developments of agricultural production in Europe, which coincides with the anthropogenic alterations of the global N cycle. The human transformation of the terrestrial N cycle leads to the understanding of the congruent need for change of the current agricultural production system among scientists and policymakers. As such, the final section discusses CA and how it is related to the dairy farming system. Additionally, the nutritional requirements of dairy intake are discussed for the purpose of understanding the calculations in *Chapter 3*.

2.1 Agricultural Development and Natural Nitrogen Cycling

Around 10.000 years ago, humans started to domesticate land and animals for the consumption of protein (Oenema et al., 2010). From the start of domestication until the eighteenth century, agricultural growth took a single course in Western Europe (Rasmussen, 2010; van Zanden, 1991). As agricultural production further developed through the centuries by innovation and the introduction of various technologies, humans became more dependent on agricultural food production for their survival (Goudsblom, 1988). The agricultural development also caused an offspring of socio-cultural development since the population concentrated itself in certain regions. The agricultural growth in history has been an instigator and consequence of population growth, and as such, has in part determined the way civilization has developed (Leigh, 2004).

In agricultural development, N has been an essential nutrient since N is often the element whose supply limits the agricultural productivity of food systems (Leigh, 2004). Although it took until the eighteenth century before science began to develop a basic understanding of the chemical principles of plant nutrition and soil fertility, older civilizations have supplied the soil with N using fertilisers, such as manure and compost, and crop rotation with leguminous crops, such as clover, which increase the N content of the soil (Leigh, 2004). Cattle were supplied with N through the feed of natural vegetation and crops grown on the fields. In return, for the provision of N_r available for crop uptake, farmers were dependent on the natural geochemical cycles of the Earth. The only source of N_r available for crop uptake was the natural N cycle. To better understand N as key limiting nutrient for agriculture prior the agricultural revolution (Savci, 2012), the three processes of which the terrestrial N cycle consists of: input, transformation, and output, need to be further explained.

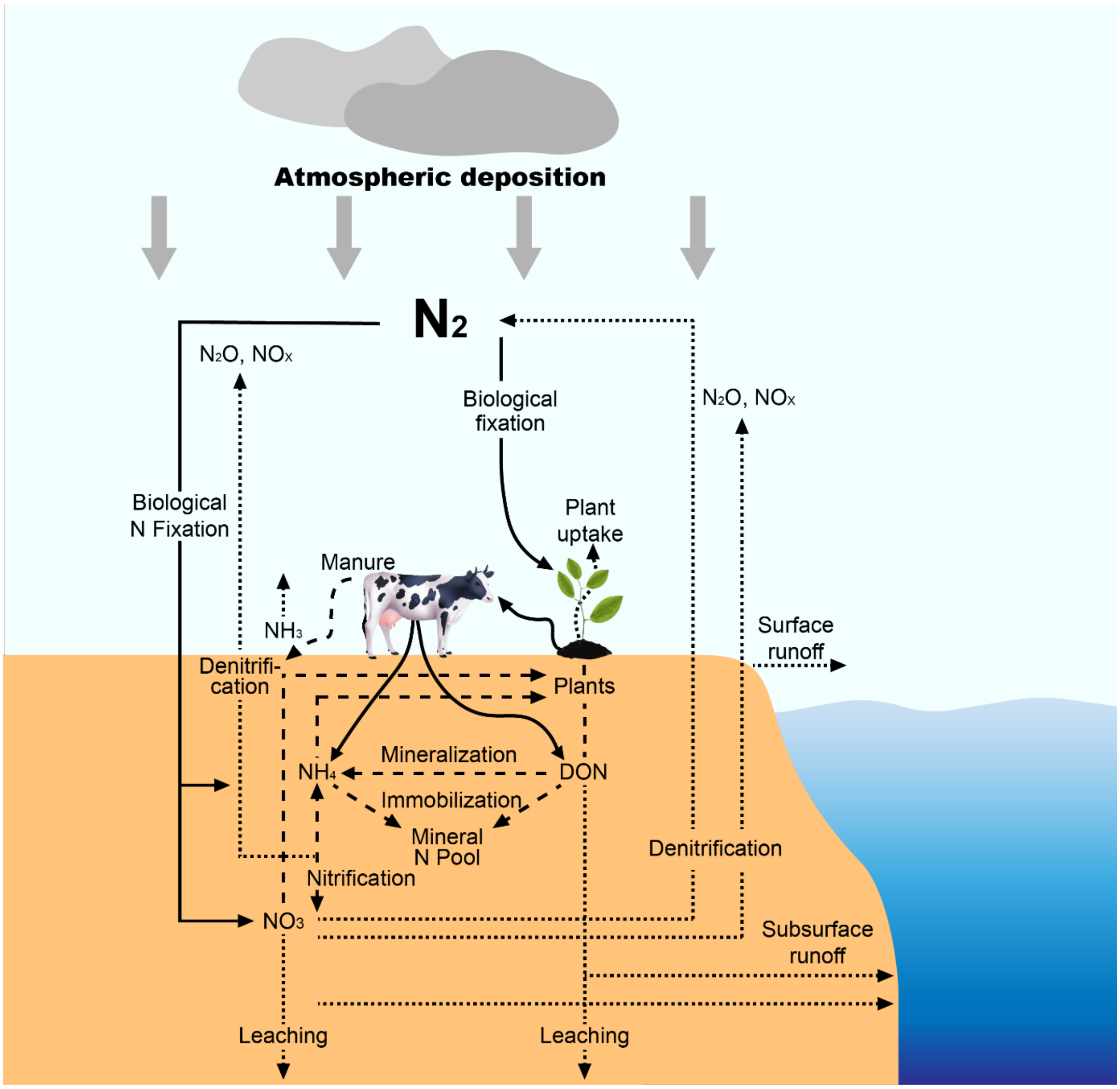

Figure 2. *Schematic representation of the terrestrial N cycle. The N inputs are represented with solid arrows, the internal fluxes with dashed arrows, and the outputs with dotted arrows. N enters the terrestrial ecosystem by the conversion of N_2 to N_r by lightning and BNF. BNF is either symbiotic, in which the atmospheric N is directly added in the root of plants, or non-symbiotic, in which the N_2 is processed into N_r by free living micro-organisms in the soil. The N_r is either assimilated by plants or lost from the terrestrial ecosystem. The N_r can be lost from the terrestrial ecosystem through NH_3 volatilization, NO_3^- leaching or denitrification, or erosion. N in the organic material of plants and animals can become available for uptake again by the decomposition of animal excretion, or plant and animal remain. The Figure is adjusted from Q. Zhu et al. (2018).*

2.1.1. Soil Nitrogen Input

In the absence of human activities, there are three sources of N_r for plant uptake: BNF, deposition and decomposition. BNF is the dominant source of reactive N_r. BNF is the process in which N-fixing micro-organisms convert the atmospheric N_2 to NH_3 by nitrogenases. There are three types of N fixing micro-organisms: non-symbiotic, associative symbiotic and symbiotic N fixers. Non-symbiotic N fixers are micro-organisms living freely in the soil, associative symbiotic N fixers are micro-organisms living in close contact with plant roots, and symbiotic N fixers are micro-organisms that are part of a mutualistic relationship in which plants provide carbon in exchange for fixed N. The highest rate of N fixation is by symbiotic N fixing micro-organisms. The N fixed by non-symbiotic N fixers, is added to the soil mineral N pool from which plants can assimilate N (X. Zhu et al., 2015). The atmospheric N_2 can also be converted to N_r through lightning. Lightning converts N_2 and oxygen into nitrogen oxides (NO_x). With rainfall, the NO_x dissolves and causes wet deposition on the soil where it becomes available for plant uptake (*Biological Nitrogen Fixation-Symbiotic and Asymbiotic*, n.d.). In addition, N becomes available for crop intake through the decomposition of plant residues, animal excretion and animal remain. Grazing animals, such as cattle, ingest the N contained in plants through their feed intake. Around 30% of the N intake is retained as live weight gain or animal products. The other 70% is excreted as urine and faeces. The excretion, and other dead organic matter, is decomposed by micro-organisms and released as dissolved organic N (DON). The DON can be converted into mineral forms of N that can be used by plants and micro-organisms (X. Zhu et al., 2015). As BNF is by far the largest natural source of N_r from the atmosphere, it was the main constrain concerning the limitation of N available in the soil for crop uptake until the twentieth century (Wooliver et al., 2019).

2.1.2. Soil Nitrogen Transformation

The largest source of N in the soil is DON. However, DON is not directly available for plant intake. Microbes in the soil break down the DON and release ammonium (NH_4^+) into the soil in a process called ammonification or mineralization (X. Zhu et al., 2015). The NH_4^+ can be either assimilated by crops, immobilized by microbial, absorbed by clay minerals, or oxidized. With immobilisation, the opposite of mineralisation, NH_4^+ is converted back to DON and is unavailable to plants again. The oxidisation of NH_4^+ is done by nitrifying bacteria that first convert NH_4^+ to N dioxide (NO_2^-) and then to NO_3^- in a process called nitrification. Denitrification is the process in which denitrifying bacteria reduce NO_2^- or NO_3^- to N_2O or N_2 (X. Zhu et al., 2015).

2.1.3. Soil Nitrogen Output

There are several sources in which N can be lost from the soil: through volatilisation, NO_x emissions, leaching, and erosion. N volatilisation is the process in which NH_3 gas is lost from the soil and returns to the atmosphere (X. Zhu et al., 2015). In the absence of human activities, volatilization is mainly related to the organic form of N called urea. Urea may originate from urine, faeces, and decay of plant materials (McNeill et al., 2007). Another form of N losses to the atmosphere is related to NO_3^- resulting from nitrification. NO_3^- is prone to loss from the ecosystem by leaching or NO_x emissions (X. Zhu et al., 2015). NO_3^- leaching is dependent on the quantity of water passing through the soil and its concentration in the soil (McNeill et al., 2007). NO_x emissions result from denitrification and depend on among others, nitrification and the NO_3^- concentration in the soil. The last source of losses to the soil is wind and soil erosion which transfers N to another part of the terrestrial ecosystem, or to the marine ecosystem (McNeill et al., 2007). Together with BNF, these sources of N losses were the main constrains for the limited availability of N_r in the soil available for crop uptake until the twentieth century (Wooliver et al., 2019). Figure 2 visualises the terrestrial N cycle.

2.2 Agricultural Development and Anthropogenic Nitrogen Cycling

The end of the nineteenth century was a turning point in history for intensive agriculture and industrial chemistry. From the mid-19th century, the European population saw an unprecedented growth rate (Leigh, 2004) coherent with the intensification of agriculture (Knibbe, 2000). Between 1880 and 1895 alone, the crop yields in the Netherlands increased by 30%. The increase in agricultural production from 1880 until 1910, often referred to as the first green revolution, was for a large part related to the increase in imports of concentrated feed, such as corn from America and linseed cakes from Russia. The use of concentrated feed for animals grew rapidly after 1880 which caused a substantial increase in livestock, and the number of cattle increased by 25% in the Netherlands. The increase in feed imports and livestock caused a boost in quantity and quality of manure and with that the shortage on fertilizers decreased (Knibbe, 2000). The rise in imports of livestock feed, also freed up land for the production of food crops within the Netherlands (Knibbe, 2000). As a result, the upsurge of feed imports changed the agricultural system in the Netherlands.

The first green revolution was also strongly related to the increasing availability of N_r. By 1834 artificial fertilizers were used widely (Leigh, 2004), originating from manure, waste from factories, city refuse and soil (Knibbe, 2000), but the availability of N_r was still limited. This changed at the end of the Industrial Revolution in Europe as an increasing fertilizer availability and application resulted from the trade of N-rich fertilizers, such as, guano, dried bird excrement and sodium nitrate originating from Peru and Chile (Melillo, 2012). The increase in fertilizer use in agriculture, combined with the availability of cheap fossil energy, transport connections, and the law of the free market, resulted in specialisation and intensification of agriculture (Oenema et al., 2010). The widespread availability of imported feed and fertilizers facilitated the departure from ‘closed system farming’ to an ‘open system farming’ where N is imported in the form of feed and fertilizers and exported in the form of crops and animal products to distant places (Melillo, 2012; van Zanden, 1991).

Another development which largely affected agricultural production, was the Haber-Bosch process. In 1903, Fritz Haber showed that it was possible to industrially produce NH_3 from the atmospheric N_2 and H_2 (Paull, 2009). In 1932, Bosch extended the process to an industrial scale (Paull, 2009). Before the discovery of the Haber-Bosch process, large amounts of fertilisers were already used in agriculture, however, these forms of fertilisers represent the recycling of N that was already fixed (Vitousek et al., 1997). The Haber-Bosch process made it possible to fix the nonreactive N_2 from the atmosphere, which eliminated the main limitation in agricultural production for those who could afford it (Paull, 2009). In Europe, the two World Wars led to the policy rationale of governments to produce as much food as possible by whatever methods, which included the widespread application of N fertilisers (Leigh, 2004). Since the discovery of the Haber-Bosch process, the worldwide industrial fixation of N has grown to an estimated magnitude of 100.000.000 tonnes per year, comparable to the estimated magnitude BNF per year (Paull, 2009). As such, the Haber-Bosch process is described as “the progenitor of the basis for modern intensive agriculture” (Paull, 2009).

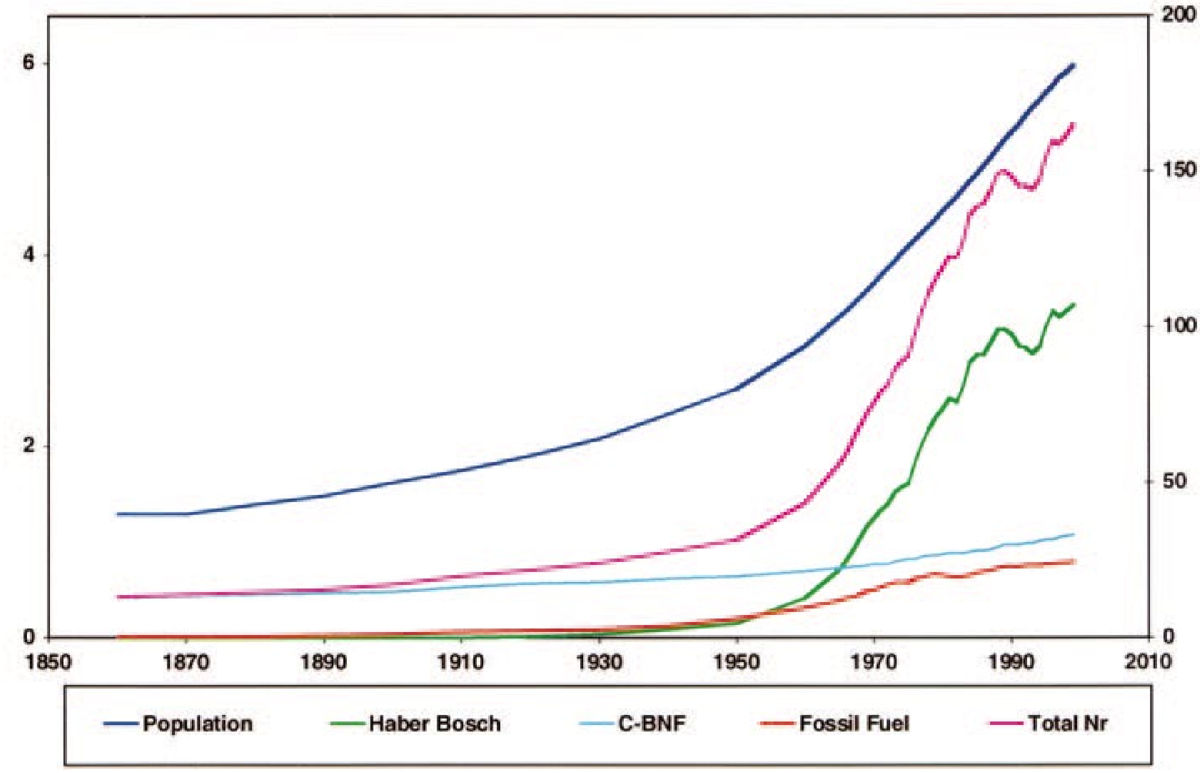

Figure 3. *This Figure displays the global population trends from 1860 to 2000 in billions on the left axis and reactive nitrogen (N_r) creation in tera-grams Nitrogen (N) per year (Tg N/year) on the right axis. The green line 'Haber-Bosch' represents N_r creation through the Haber-Bosch process, including the production of ammonia (NH_3) for nonfertilizer purposes. The blue line called 'C-BNF' represents N_r creation from cultivation of legumes, rice, and sugarcane. The orange line 'Fossil fuel' represents N_r created from fossil fuel combustion. The pink line 'Total N_r' represents the sum created by these three processes. Retrieved from Galloway et al. (2003).*

The impactful changes in agriculture from the nineteenth century until now, have led to, among others, economic efficiency, and welfare gains. The downside, however, is the environmental degradation these agricultural activities have induced (Leigh, 2004). Although the atmospheric N_2 is not harmful to the environment, the widespread release of the compound's NO_x and NH_3 in the air do have negative environmental effects (*Stikstof* , 2021). Industrial N fixation, fossil fuel combustion, the cultivation of crops which support symbiotic BNF, biomass burning, land-clearing and conversion, and the drainage of wetlands, have all contributed to an increase in the concentration NO_x and NH_3 in the atmosphere (See Figure 3) (Paull, 2009). Within the atmosphere, the accumulation of NO_x and NH_3 have negative consequences for the production of aerosols, ozone depletion, and climate change (Galloway et al., 2003; Gruber & Galloway, 2008). NO_x and NH_3 eventually deposit on the ground through precipitation (wet deposition) or through fixation (dry deposition). The deposition can increase productivity, but also negatively affects the terrestrial ecosystem, by, among others, eutrophication, habitat degradation and decreased biodiversity and species richness (Galloway et al., 2003; Gruber & Galloway, 2008).

2.3 Circular Agriculture in Dairy Farming

The negative environmental consequences related to the departure from 'closed system farming' to 'open system farming', has led to the vision of the Ministry of LNV for CA in 2018 (Grumbine et al., 2021). CA is "agriculture with the lowest possible harmful emissions to the environment and the highest possible resource efficiency" (Vrolijk et al., 2020). In linear production systems, natural resources are converted into products and eventually waste (Barros et al., 2020). A circular economy, based on the fundamentals from industrial ecology (Barros et al., 2020), eliminates waste by maintaining components, materials, and products at their highest value instead of importing resources from outside the system (FAO, 2017; Scholten et al., 2018). Currently, the dairy farming system is not circular as large quantities of N are imported into and exported from the system.

Figure 4 displays a schematic representation of the N flows in the dairy farming system. Dairy cattle take in N embedded in feed of which 21% to 38%, is transferred to milk and weight, and the remainder is excreted as faeces and urine (Mijnrantsoenwijzer.nl, 2014). The milk is exported from the dairy farming system, and as such a part of the N leaves the system. The N in excretion is either emitted or content of manure depending on the metabolic activity, the production system, the feed intake, and the climatic conditions (Dolman et al., 2019). In dairy farming, the largest share of the manure excreted by dairy cattle is applied to land of dairy farms. Another share of the manure is exported and applied by arable farms, and only a small share is processed and sold (Riechelman, 2019). A part of N is emitted in storage, handling, or land application of manure (LPELC, 2019; C. A. Rotz et al., 1999), or lost through leaching, denitrification, or soil erosion (Bouwman et al., 2009; Dolman et al., 2019). Dairy farmers also import large quantities of N through the application of chemical fertilizers to the soil (Bouwman et al., 2009; Dolman et al., 2019). The N_r that becomes available in the soil as a result of fertilization can be assimilated by crops and stored in the root biomass, root zone, harvestable product, plant residue and shoots (Fuchs, 2020). Only the N in the harvestable product is removed from the field, the rest is left on the land. The yielded crops are stored and afterwards either fed to dairy cattle or sold. The largest imports in the system are N embedded in feed and in chemical fertilizers, and the largest export out of the system is N in the form of milk. To reach CA in the dairy farming in the national, European, or global scope, these imports and exports need to be adjusted.

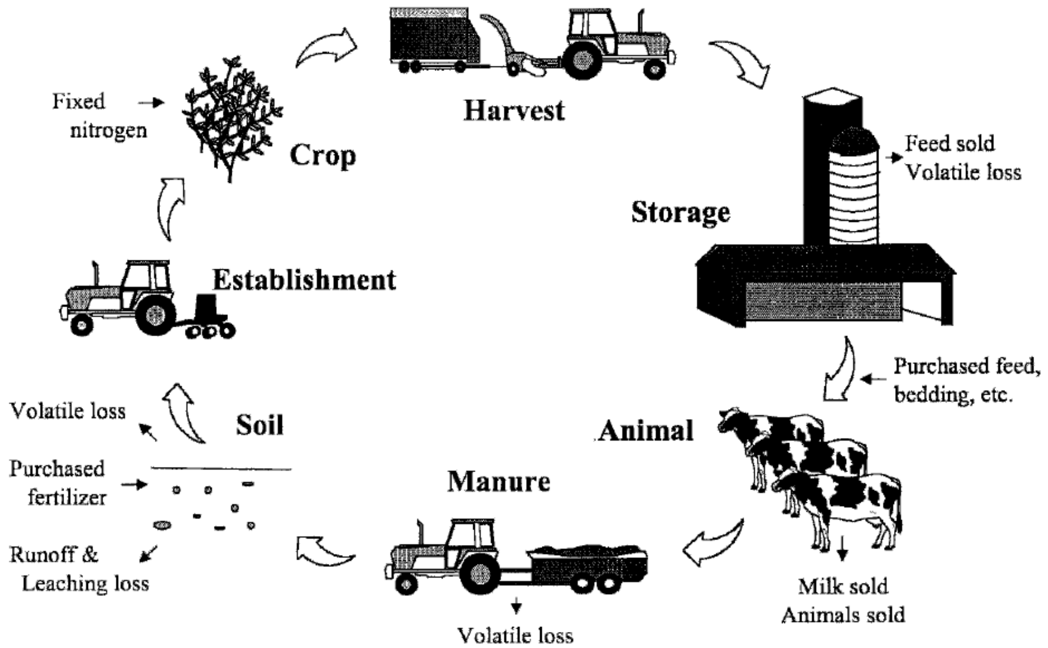

Figure 4. A schematic representation of the N flows in the dairy farming system. Cattle is fed with N by either produced feed in the dairy farm or purchased feed. The N in milk is exported from the system, and the N in manure is used on the soil for the production of crops. Meanwhile part of the N is lost through volatilization and leaching. N is also added to the soil through chemical fertilizers. The N in the harvestable part of crops is harvested and either stored or sold. Retrieved from Rotz et al. (1999).

The feed for dairy cattle is produced across the globe, ranging from Dutch maize silage to European barley and Brazilian soy (Nevedi, 2018). Dairy cattle take in N through their feed in the form of Crude Protein (RE), which consist of 16% N (C. A. Rotz et al., 1999). The feed intake of dairy cattle is composed of ~70% of roughage, ~25% of concentrate feed and ~5% of moisture rich feed (van Bruggen & Gosseling, 2019b; *Welke Dieren Fosfaatrechten* , 2020). The roughage consists of pasture grass, grass and hay silage and green maize, also called silage maize (van Bruggen & Gosseling, 2019b). The roughage is all produced within the Netherlands and for a large part on dairy farms. 10% of the concentrate feed is singular feed, and 90% is compound feed. Compound feed consists of processed products, including raw products, co-products, minerals and additives, and fats and oils (Nevedi, 2018). Singular feed are single raw materials, and often includes the same feed types as of which compound feed consists of (van Bruggen & Gosseling, 2019b). Examples of concentrate products are soy meal, maize, wheat, sunflower meal, and molasses. The products in concentrate are for a large part imported from outside the Netherlands. Especially the products high in protein are imported from abroad (Silvis et al., 2021). The moisture rich feed consists of by-products of the food industry, such as beet pulp and beer brush. The origin of the moisture rich feed is both Dutch and imported (OPNV, 2018). Feed intake and composition, and its nutritional value, determine the milk production and excretion of dairy cattle.

Cows belong to the category ruminants and, as such, cows can convert plant-based material, unusable for humans, into high-quality products (C. A. Rotz et al., 1999). **Figure 5** visualises the nutrient composition of a cow's diet. The feed consists of dry matter (DS) and water. The DS is composed of organic matter (OM) and mineral substances (ash). The OM contains the nutritional value for dairy cattle and contains the energy (from crude fat and sugar yeast) protein (from crude protein), and structure (from crude cellulose) that a dairy cow needs for milk production, growth, and body maintenance (Verhoeven & Smale, 2014).

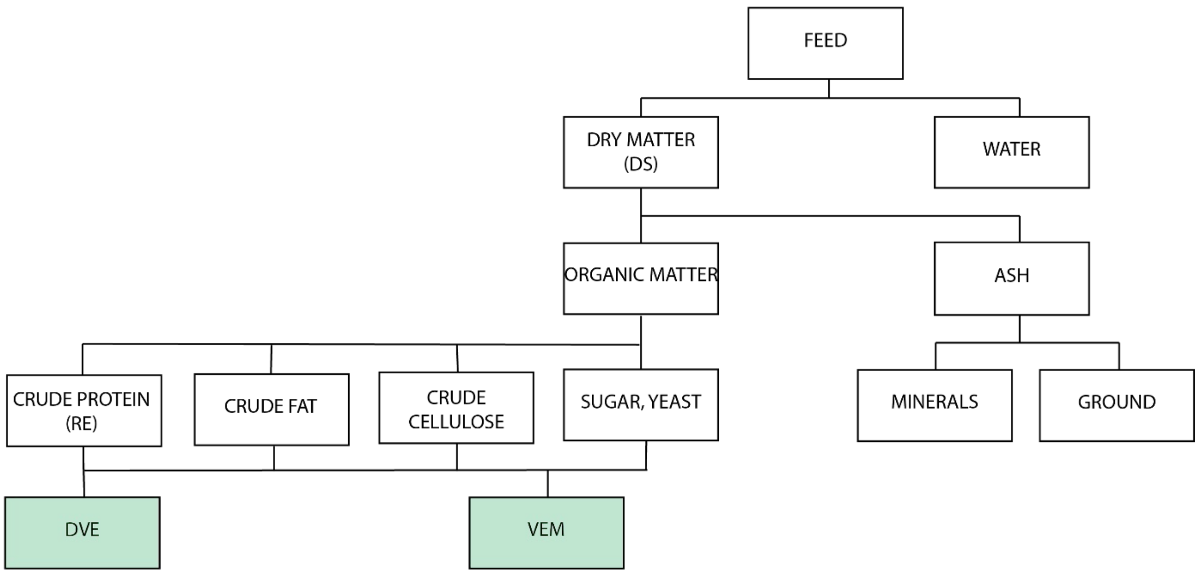

Figure 5. *Schematic representation of the nutrient composition of feed for dairy cattle. Feed consists of dry matter (DS) and water. The DS consists of Organic Matter (OM) and mineral substances. The OM contains the nutritional value of the feed for dairy cattle as it contains energy, protein, and structure. The energy content of feed is measured in energy need per unit milk (VEM), and the protein content of feed is measured in gut digestible protein (DVE). The Figures is based on van Liefferinge (2011).*

One of the most important functions of feed is the provision of energy. Dairy cattle need energy for maintenance, growth, gestation, and milk production. A shortage of energy can reduce milk production, decrease the protein content of milk, and result in health and fertility issues. On different levels in the digestion of cows, energy is lost in the form of heat, faeces, gasses, and urine. The energy which is not lost in the digestion and metabolism, and which is available for production, is called the net energy. In the Dutch agricultural sector, the net energy intake of dairy cattle is expressed as the energy need per unit milk (VEM) (van Liefferinge, 2011; Verhoeven & Smale, 2014).

The intake of RE through feed, is directly related to the N intake since RE contains about 16% N. RE is an important building block of the body's tissue, bones, and hair. For lactating cows, RE is also important for the production of milk. A shortage of protein can reduce milk production, or reduce the milk protein content, while a surplus of protein can negatively affect health, fertility, and the environment (Hubrecht et al., 2013). The higher the RE intake of cattle, the higher the N-emissions are (Engelen, 2020). The RE in the diet is broken down by micro-organisms in the rumen into peptides, amino acids, and NH_3. The amino acids are used by bacteria to produce microbial protein. The fraction of the microbial protein, which is not lost but available for digestion, is called the gut digestible protein (DVE) and covers the need of amino acids for maintenance, growth, pregnancy, and lactation (Hubrecht et al., 2013).

3. Methods

To understand how reduction in N embedded in feed imports may affect cattle stock, dairy production, and N emissions, the methods in this section are utilised. First, to understand the N flows in dairy production and the associated inputs and outputs, a model of N flows is described which captures the key flows, the conversion, and the losses of N at each stage. Second, to understand how changes in import may impact N cycling in the Netherlands associated to dairy production, three scenarios are described which allow an exploration of circularity on three different scopes.

3.1 The Dairy Farming Model

A model was developed to quantify the effects in N flows through the dairy sector for the three defined scenarios (section 3.2). The method is a static account of annual N flows and emissions in the dairy farming sector (le Noë et al., 2017; Schils et al., 2005) and is used for a comparative scenario analysis to derive direct and indirect effects of system interventions (Großmann & Hohmann (2019). As such, scenarios can be a useful tool for decision-making (Xiang & Clarke, 2003). In a static model the behaviour of a system is time-independent as the results provide a 'snapshot' of a systems response to specified input conditions and equations (*Simulation - Static vs. Dynamic Models*, n.d.). The basic idea behind the model is to describe the N cycle of dairy farming on the national level to analyse the overall effect of decision on the scope of circularity on N emissions. The model is based on: (1) feed-excretion relationships in dairy cattle as described by RVO (2019) and Šebek et al. (2017), (2) nitrogen-roughage relations described by Akkerbouwgewassen; Productie Naar Regio (2021), Landbouw; Gewassen, Dieren En Grondgebruik Naar Bedrijfstype, Nationaal (2021), Mineralenbalans Landbouw (2020), Nutrienten (2021) and RVO (2020a), and (3) feeding requirements as described by Blok & Spek (2018) and van Liefferinge (2011). These relations allow for calculation of animal and plant production in 2018. The model was developed as a spreadsheet using Microsoft Excel.

Figure 6 visualises the N flows in the static model and its sub-system components. The model consists of two systems: the dairy farming system and the international feed production system. The dairy farming system consists of the sub-systems (i) the dairy production system in the Netherlands and (ii) the roughage production system in the Netherlands, and the international feed production system consists of the sub-systems (iii) the dairy cattle feed production system in European countries, excluding the Netherlands, and (iv) the dairy cattle feed production system of the world, excluding European countries. Each sub-system has input and output of N, and there are flows of N between the different sub-systems. In the following sections the processes in each sub-system are explained in more detail and the relevant data used to capture the N flows are outlined.

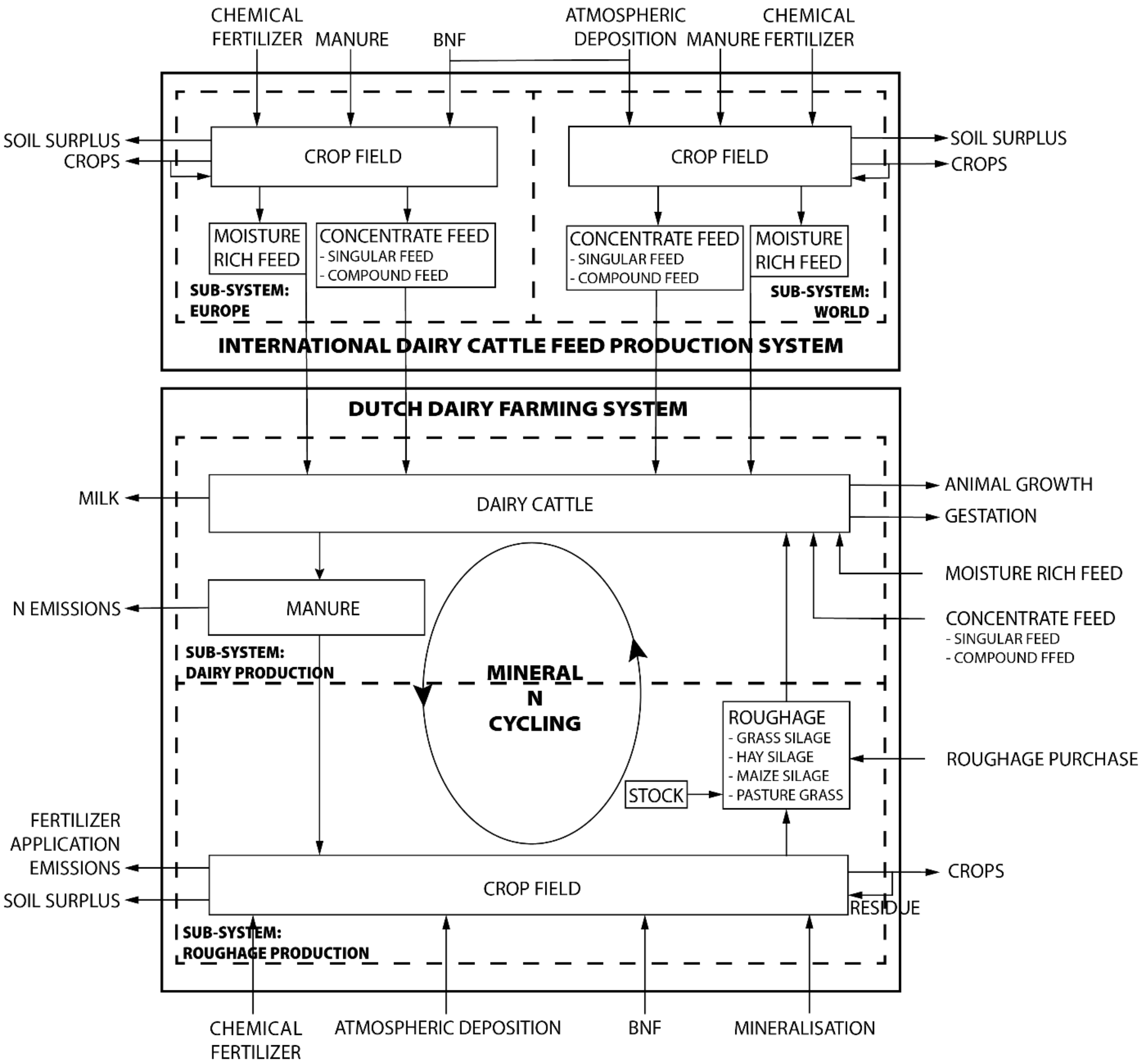

Figure 6. *Schematic representation of the N flows in the Dutch production system related to dairy. The model consists of two systems: the Dutch dairy farming system and the international dairy cattle feed production system. These two systems in turn consist of four sub-systems (i) dairy production, (ii) roughage production, (iii) European feed production, and (iv) global feed production. The dairy production system (i) consists of N input in the form of feed intake (concentrate feed, moisture rich feed and roughage) by cattle, and N output in the form of animal growth, milk, gestation, and manure. A part of the N in manure is lost in the form of N emissions. The roughage production system (ii) consists of input of N in the form of chemical fertilizer, manure, BNF, atmospheric deposition, mineralisation, and crop residues. The output of N in the system is in the form of yield of roughage and crops other than roughage, N application emissions and soil surplus. There is mineral N cycling between the dairy production system and the roughage production system as the manure of cattle is used as fertilizer on the field to produce the roughage for cattle. The European feed production system (iii) and the global feed production system (iv) have N input through chemical fertilizer, manure, BNF, atmospheric deposition and crop residues, and N output in the form of soil surplus, dairy cattle feed, and other crops.*

3.1.1 Required Input Data

This section elaborates on the required data and its sources used in this thesis. Besides the data sources named in the section below, relevant meta-data was collected to judge the methods, make data selections, and relate the results to relevant literature. The literature was mainly collected through the search engines Google Scholar and World Cat. This section, first, discusses the required data and sources for the dairy farming system. The dairy farming system consists of roughage production and of dairy production. Second, the required data and sources for international feed production of dairy feed are discussed. The international dairy cattle feed production system consists of European feed production, excluding the Netherlands, and global feed production, excluding Europe.

The Dairy Farming System

Dairy cattle require input of N in the form of feed. The feed of dairy cattle consists of roughage, moisture rich feed, compound feed and singular feed. The average DS intake per year for milk cows and young stock of moisture rich feed, grass silage, pasture grass, maize silage and concentrate is retrieved from van Bruggen & Gosseling (2019). The compound feed is provided to dairy cattle in the form of different chunks differing in, among others, protein content. The average feed commodities of which these compound chunks consist in 2018 is retrieved from personal communication (F. Gort, personal communication, March 3, 2021). Which chunks are provided to which dairy cattle category and the ratio in which these are fed is determined through personal communication (W. van Straalen, March 16, 2021). The commodities of which singular feed consists of are based on de Kleijne et al. (2018) and Remmelink et al. (2020). The commodities of which moisture rich feed consists of is provided for by the Consultation Group for Moisture Rich Feed Producers (OPNV) for cattle, including dairy and meat cattle (OPNV, 2018). The ratio of feeding moisture rich feed to dairy cattle is assumed equal to the total moisture rich feed provision to cattle in 2018 (OPNV, 2018). The quantity import was converted to nutrients using the conversion factor of nitrogen [g N/kg] retrieved from Blok & Spek (2018). The part of the moisture rich feed and concentrate feed which is produced within the Netherlands is determined by the method described later in this section.

The output of the diary production sub-system consists of N fixed in manure, gestation, growth, and/or milk. All outputs of this sub-system are dependent on the size of the cattle stock. The size of the cattle stock is in turn dependent on the energy and protein requirement per cow and the total available energy and protein in the feed. The energy needs and availability are expressed in VEM, and the protein need, and availability is expressed in DVE and RE (see section 2.3). The availability of DVE and VEM is determined by converting the products in the feed composition to energy and protein by retrieving the energy and protein content of the feed products in the cow's diet from Blok & Spek (2018). The DVE and VEM requirements per cow are calculated as described in section 3.1.2 where certain factors are presumed equal to the situation in 2018. These presumptions concern the milk production per cow, the number of grazing days and hours, the period of lactation, the shed type, and the replacement rate (Remmelink et al., 2020; *StatLine*, n.d.; van Bruggen & Gosseling, 2019b). The RE requirement per quantity DS is retrieved from Verhoeven & Smale (2014). With the size of the cattle stock, the fixation of N in growth, gestation, milk, and manure, as well as the N emissions from manure, can be calculated using the equations described in 3.1.2.

The input of the roughage production sub-system consists of N in the form of manure, organic fertilizer, chemical fertilizer, BNF, atmospheric deposition, mineralisation, and residues. The average BNF, deposition and mineralisation on arable land of dairy farms is retrieved from Agrimatie for 2018 in kg N per hectare (ha) (*Nutrienten*, 2021). The total scope for the use of fertilizers is strongly related to legislation and policy concerning fertilizers and manure (Hoogeveen et al., 2019). The maximum N utilisation space is dependent on the cultivated area of each crop and the crop specific N norms (RVO, 2020). The cultivated area of each crop is retrieved from the Dutch national statistical office (CBS), and the crop specific N norms is retrieved from the Dutch National Office for Entrepreneurs (RVO) (RVO, 2020). The maximum N utilisation space is used in this thesis, except for grassland for which the average N utilisation in 2018 is retrieved from the research database of the Wageningen University

(Agrimatie) (*Nutrienten*, 2021).The N utilisation space consists of chemical fertilizers, organic fertilizer other than manure, and the effective part of the N in manure. This effective part of N is the share of N in manure that (directly) becomes available for crop uptake. In manure a relatively large share is lost in application or is only available on a later stage. As such, the so-called working coefficient is 0,6, while, in comparison, the working coefficient of chemical fertilizers is 1 (RVO, 2018; van Brouwershaven et al., 2017). To determine the application of fertilizers, first the amount of manure applied to the soils is determined. The manure excreted in the pasture is directly applied on grassland, and manure is added until the N utilisation space for manure is reached. Following the EU nitrate directive (1991), the maximum manure utilisation space on soils is 170 kg N per ha (Hoogeveen et al., 2019). In 2018, around 82% of the Dutch dairy farms applied for derogation, which allows a maximum use of manure of 230 or 250 kg N per ha depending on the soil type. The total legal N manure utilisation space on all dairy farms was 202.900.000 kg N in 2018 (*Dierlijke Mest; Productie En Mineralenuitscheiding; Bedrijfstype, Regio*, 2021; RVO, 2021). According to Agrimatie, the average fertilization on dairy farms with manure was 236,77 kg per ha in 2018 (*Nutrienten*, 2021), which comes down to 201.102.434 kg N applied on dairy farms through manure in 2018. When the manure utilisation space is reached on grassland, chemical fertilizer is applied to reach the maximum N utilisation space of the crop calculated based on the legal working coefficient (RVO, 2018). This process is replicated first for maize silage and then for the other cultivated crops on dairy farms to determine the fertilization in the roughage production system. An overview of the cultivated crops, the corresponding area in ha, the maximum utilisation space and N application used in this thesis on dairy farms in 2018 is supplied in Appendix A.1 .

Table 1. *The cultivated crops on dairy farms in 2018 with the cultivated area in ha retrieved from StatLine , the maximum N utilisation space retrieved from the RVO, and the fertilizer input utilised in this thesis (Dierlijke Mest; Productie En Mineralenuitscheiding; Bedrijfstype, Regio, 2021; RVO, 2020). For fodder crops, arable farming and horticulture, the utilised fertilizer input is equal to the maximum N utilisation space. For grassland, the average N application for 2018 on dairy farms is retrieved from Agrimatie (Nutrienten, 2021).*

Cultivated Crops	Area (Ha)	Maximum N Utilisation Space (Kg N/Ha)	Fertilizer Input (Kg N/Ha)
Grassland and fodder crops	**827.132,36**	**342**	**260**
Grassland	**718.017,85**	**366**	**272**
Grassland Temporary	1.707.02,60	310	287
Grassland Permanent	511.165,97	385	287
Grassland Natural	36.149,28	0	0
Fodder crops	**109.114,51**	**183**	**183**
Maize silage	106.731,45	160/185	185
Fodder beets	1.036,99	165	165
Lucerne	945,42	40/0	0
Other green fodder crops	400,65	150	150
Arable farming	**21.321,69**	**180**	**180**
Horticulture	**903,70**	**165**	**165**

The output of the roughage production sub-system consists of roughage crops, other crops, N application emissions, and soil surplus. The soil surplus is calculated with the method described in section 3.1.2. The average N application emissions on dairy farms in 2018, is retrieved from Agrimatie (*Nutrienten*, 2021). The crop yields are determined by dividing the total N yield by the cultivated area retrieved from CBS StatLine (*Akkerbouwgewassen; Productie Naar Regio*, 2021; *Mineralenbalans Landbouw*, 2020). Since all roughage for dairy cattle is produced within the Netherlands (Silvis et al., 2021), the difference between roughage intake and roughage production on dairy farms is assumed to originate either from stock on dairy farms or purchased from arable farming.

The International Dairy Cattle Feed Production System

The input of the non-Dutch feed production system is not considered in this research. The outputs of the two-subsystems are concentrating, consisting of singular feed and compound feed, and moisture rich feed for the Dutch dairy cattle. A share of the concentrate and moisture rich feed is produced within the Netherlands. To determine the origin of the feed commodities of which the average feed composition in 2018 consists of, the Dutch production and import data for these commodities is utilised. The production data is obtained from the online public statistical database of the Food and Agricultural Organisation of the United Nations (FAOSTAT), the online public statistical database of the EU (EUROSTAT) and the online public statistical database of the CBS (StatLine) (Eurostat, 2021; FAOSTAT, 2021; *StatLine*, n.d.). The import data is obtained from FAOSTAT for the year 2018 (FAOSTAT, 2021) and contains trade information (i.e., trade from country 1 to country 2) in the metric quantity [tonne]. 2018 is the most recent year available for the data on the feed composition of compound feed.

The data on feed composition combined with production and import data of the Netherlands, determined the countries in the trade network. All countries were ordered '*regional*' or '*international*', where *regional* includes all countries on the continent Europe and *international* all countries in the world excluding European countries. The data on feed imports was converted to a proportional distribution. If available, this distribution was adjusted to the proportional distribution of feed import retrieved from de Kleijne et al. (2018), Nevedi (2018) and van Krimpen & Cormont (2019). If not available, the distribution of feed consumption was assumed the same as the proportional distribution of feed imports (See Figure 7) (Kastner et al., 2011). Some products can be re-exports produced in third countries. This is the case when export minus the production results in a positive number (Thissen et al., 2015). In that case, the trade flow is re-assigned to the original country in which a certain good is produced. It is assumed that re-exports follow the same trade pattern as the existing bilateral trade flows. The production and trade data are retrieved from FAOSTAT and EUROSTAT. Some countries export such small quantities that the proportional share of the feed product is less than 0,05%. As such low percentages influence trade relations minimally, these countries are excluded from the bilateral trade tables of goods.

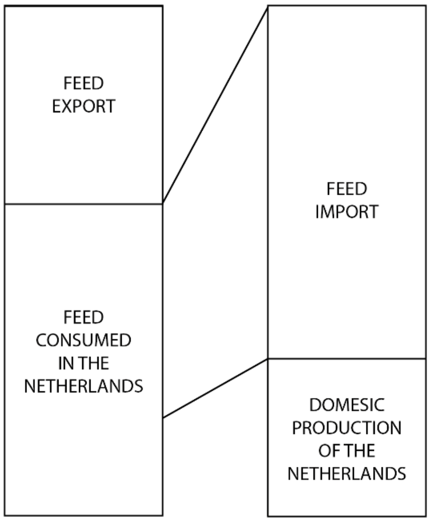

Figure 7. *Visualisation of the basic assumption underlying the presented method concerning feed imports. The feed products consumed in the Netherlands originate in proportional shares from the country's imports and own domestic production, unless proportional data was available in literature. Figure retrieved from Kastner et al. (2011).*

3.1.2 Data Calculations

This section introduces the equations to quantify the N flows through the dairy farming system in the Netherlands. In this thesis there are three dairy cattle categories (DCC) considered: milk cows (MC), young stock younger than 1 year (YS<1), and young stock older than 1 year (YS>1). MC are the dairy cattle which have calved at least one time and are kept producing milk or breeding of cattle for the dairy farming industry. YS<1 is the female young stock younger than 1 year which are kept in the dairy industry and calves from milk cows between 0 and 14 days old. YS>1 is the female young stock older than 1 year in the dairy farming industry (*Welke Dieren Fosfaatrechten* , 2020). The male young stock and breeding bulls are not considered in this research due to their small numbers and insignificance for milk production. Equations with the subscript *DCC* should be separately calculated for each DCC. Equations with the subscript *MC, YS<1 or YS>1* apply to a specific DCC only. Equations with no specification of a DCC in the subscript applies to the entire dairy cattle stock. The equations for N intake, N fixation and N excretion are retrieved from Handreiking Bedrijfsspecifieke Excretie Melkvee (2019) and Šebek et al, (2017), where they are used for farm-level calculations of the N emissions. The equations for VEM and DVE requirements are retrieved from Duinkerken & Spek (2016).

The section starts with the equations for the dairy production sub-system, in which the fixation of N in growth, gestation, milk production and excretion are calculated based on the intake of N through feed. The section proceeds with the equations related to the size of the cattle stock based on the VEM and DVE requirements and intake. Then, the section advances with the equations for the roughage production sub-system, in which the soil surplus and chemical fertilizer application are calculated.

Dairy Production Sub-system

To calculate the size of the flows in the dairy production system for scenarios A, B and C the equations listed below can be utilised.

Nitrogen Balance in Dairy Cattle

The main N flows in the dairy production sub-system is the input of feed, and the output of fixation in milk, growth and gestation, and excretion of manure (See Figure 6). The N balance in dairy cattle can be described by equation 1. The intake of N embedded in feed is calculated with equations 2 and 3, the fixation of N is calculated with equations 4 to 8, and the excretion of N by dairy cattle is calculated with equations 9 to 13.

$$Nintake = Nfixation + Nexcretion \qquad \textit{(Kg N/year) (Eq. 1)}$$

Nexcretion = Total amount of N in the excretion of dairy cattle, consisting of faeces, urine and including feeding losses in 2018 (Kg N/year)

Nintake = Total amount of N fed to dairy cattle, including average feeding losses of 2% compound feed, 3% moisture rich feed, 2% milk, and 5% conserved roughage in 2018 (Kg N/year)

Nfixation = Total amount of N fixed in the growth, gestation, and milk production of dairy in 2018 (Kg N/year)

Nitrogen Intake

The total N embedded in feed fed to dairy cattle called N intake. The total N intake of dairy cattle is calculated with equation 2 by adding the N intake of all three DCC. With equation 3, the N intake per DCC can be calculated by multiplying the quantity DS intake (in kg) with the N content per feed category and, subsequently, adding the total N of all feed categories. In scenario A, the quantity DS intake of feed commodity *nx* is equal to the global production of this commodity, in scenario B, the DS intake of commodity *nx* is equal to the European production of this commodity, and, in scenario C, the DS intake of commodity *nx* is equal to the national production of this commodity. In Table 2, the DS intake and the N-content of the different feed categories is shown for the year 2018. Subsequent equations to calculate N intake can be found in Appendix B.1 Nitrogen intake.

$$Nintake = Nintake_{MC} + Nintake_{YS<1} + Nintake_{YS>1} \qquad \textit{(Kg N/year) (Eq. 2)}$$

$$Nintake_{DCC} = Ncont_{n1} + Qfeed_{n2_{DCC}} \cdot Ncont_{n2} + Qfeed_{nx_{DCC}} \cdot Ncont_{nx}$$

(Kg N/year) (Eq. 3)

$Qfeed_{nx\ DCC}$ = The total quantity DS of feed commodity *nx* provided to a specific DCC in 2018 (Kg/year).

$Ncont_{nx}$ = The N content of feed commodity *nx* provided to dairy cattle (Kg N/Kg DS).

Table 2. *The N-content of different feed types, and the quantity dry matter (DS) fed to the three dairy cattle categories in 2018. The DS quantity includes 5% losses for conserved feed, 3% losses for moisture rich feed, 2% losses for singular and compound feed, and 2% losses for milk. The three livestock categories are milk cows (MC), young stock younger than 1 year (YS<1) and young stock older than 1 year (YS>1). The data on quantity DS and N content of milk, pasture grass, maize silage, grass and hay silage, and moisture rich feed are retrieved from van Bruggen & Gosseling (2019). The N content of compound feed, singular feed and moisture rich feed commodities is retrieved from Blok & Spek (2018) and is in alignment with the average N content the feed type from van Bruggen & Gosseling (2019).*

Feed type:	**N content (g/Kg DS)**	**DS Intake MC (Kg/cow/year)**	**Ds intake YS<1 (Kg/cow/year)**	**Ds intake YS>1 (Kg/cow/year)**
Milk(powder)	5,47	0,0	200,0	0,0
Singular Feed	48,29	206,0	31,5	9,7
Compound Feed	28.13	1854,0	314,9	87,7
Moisture Rich Feed	25,42	348,0	0,0	0,0
Grass and Hay Silage	29,6	2841,8	870,5	1810,3
Maize Silage	11,3	1594,4	143,5	116,0
Pasture Grass	31,2	781,5	136,2	732,3

Nitrogen Fixation

The total N fixed in dairy cattle called Nfixation, is calculated with equation 4 by adding the total N fixation for each DCC. Generally, the fixation of N is calculated with equation 5 by multiplying the quantity animal product (in kg) with the N content of the product (in kg N/kg). The product in which N is fixed differs per DCC. For YS<1, the N is fixed in growth (equation 6), for YS>1, N is fixed in growth and gestation (equation 7), and for MC, N is fixed in milk, gestation, and growth (equation 8). In Appendix B.2 Nitrogen Fixation, subsequent equations to calculate N fixation are provided.

The total fixation of N in dairy cattle is calculated with the following equation:

$$Nfixation = Nfixation_{YS<1} + Nfixation_{YS>1} + Nfixation_{MC} \qquad \textit{(Kg N/year) (Eq. 4)}$$

The general equation for the fixation of N in dairy cattle is calculated with the following equation:

$$Nfixation_{DCC} = Qanimalproduct_{nx\,DCC} \cdot Ncontanimalprod_{nx} \qquad \textit{(Kg N/year)(Eq. 5)}$$

$Qproduct_{nx\ DCC}$ = The quantity animal product *nx* for a specific DCC in 2018 (Kg/year)

$Ncontprod_{nx}$ = The N content of animal product *nx* (Kg N/Kg product)

The N fixation in YS<1 is calculated with the following equation:

$$Nfixation_{YS<1} = N_{growth1} \qquad \textit{(Kg N/year) (Eq. 6)}$$

Ngrowth1 = The total N fixed in growth of young stock between age 0 (birth) and age 1 (Kg N/year)

The N fixation in YS>1 is calculated with the following equation:

$$Nfixation_{YS>1} = N_{growth2} + N_{gestation1} \qquad \textit{(Kg N/year) (Eq. 7)}$$

Ngrowth2 = The total N fixed in growth of young stock between age 1 and the first calving in 2018 (Kg N/year)

Ngestation1 = The total N fixed in gestation of young stock older than 1 year in 2018 (Kg N/year)

With the following equation, the N fixation in MC can be calculated:

$$Nfixation_{MC} = N_{growth3} + N_{gestation2} + N_{milk} \qquad \textit{(Kg N/year) (Eq. 8)}$$

Ngrowth3 = The total N fixed in growth of milk cows in 2018 (Kg N/year)

Ngestation2 = The total N fixed in gestation of milk cows in 2018 (Kg N/year)

Nmilk = The total N fixed in the milk production of milk cows in 2018 (Kg N/year)

Nitrogen Excretion

The total gross N excretion of dairy cattle is calculated with equation 9 by adding the N excretion of the three DCCs. Per DCC, the gross N excretion is calculated with equation 10 by subtracting the fixation of N from the intake of N embedded in feed. The net N excretion is the N excreted in manure after subtraction of gaseous losses and is calculated with equation 11. The total gaseous loss for dairy cattle is calculated with equation 12 by adding the gaseous losses of each DCC. The gaseous losses consist of NH_3 emissions from manure in the shed, other N emissions from the shed, and from N emissions from external storage of manure (Equation 13). In Appendix B.3 Nitrogen Excretion subsequent equations to calculate the N excretion is supplied.

The total (gross) N excretion of dairy cattle is calculated with the following equation:

$$Nexcretion = Nexcretion_{MC} + Nexcretion_{YS<1} + Nexcretion_{YS>1}$$ *(Kg N/year) (Eq. 9)*

The gross N excretion for the DCCs is calculated with the following equation:

$$Nexcretion_{DCC} = Nintake_{DCC} - Nfixation_{DCC}$$ *(Kg N/year) (Eq. 10)*

The net N excretion is calculated with the following equation:

$$Nexcretion_{net\,\mathrm{DCC}} = Nexcretion_{\mathrm{DCC}} - Ngass_{\mathrm{DCC}}$$ (Kg N/year) (Eq. 11)

$Nexcretion_{net\ DCC}$ = The net N excretion, or N in manure after subtraction of gaseous losses, of a DCC in 2018 (Kg N/year)

$Ngass_{DCC}$ = The gaseous losses from manure in the shed and external storage for a DCC in 2018 (Kg N/year)

The total gaseous N losses of dairy cattle is calculated with the following equations:

$$Ngass = Ngass_{MC} + Ngass_{YS<1} + Ngass_{YS>1}$$ *(Kg N/year) (Eq. 12)*

$$Ngass_{DCC} = Nemission_{NH3\,DCC} + Nemission_{stable\,DCC} + Nemission_{storage\,DCC}$$ *(Kg N/year) (Eq. 13)*

$Nemissions_{NH3\ DCC}$ *= The gaseous NH_3 emissions from manure in the shed per DCC in 2018 (Kg N/year)*

$Nemission_{stable\ DCC}$ = The other gaseous N emissions than NH_3 from the shed per DCC in 2018 (Kg N/year)

$Nemission_{storage\ DCC}$ = The gaseous N emissions from external storage per DCC in 2018 (Kg N/year)

Quantity Livestock

The outputs of the dairy production system are dependent on the size of the cattle stock (See Appendices B.2 Nitrogen Fixation and B.3 Nitrogen Excretion). The size of the cattle stock in scenario A is retrieved from statistical data for 2018. The sizes of the cattle stock in scenario B and C are calculated by the number of cattle that can be provided with enough VEM and DVE embedded in feed. The total VEM availability in feed is divided by the VEM requirement per cow (equation 15) and the total DVE availability in feed is divided by the DVE requirement per cow for a specific DCC (equation 16). The minimum number of cows that can be sustained from the VEM and DVE in feed determines the cattle stock in the scenario (equation 14). The total availability of VEM and DVE is calculated with equations 17 and 18 and the VEM and DVE requirement per cow is calculated with equations 19 to 24.

The quantity dairy cattle are calculated for each DCC separately. Subsequent equations are provided in Appendix B.4 Livestock Quantity.

$$QDCC_{DCC} = MIN(QDCC_{VEM}, QDCC_{DVE}) \quad \text{(cows) (Eq. 14)}$$

$$QDCC_{VEM\,DCC} = VEMavailbility_{DCC}/VEMrequirement_{DCC} \quad \text{(cows) (Eq. 15)}$$

$$QDCC_{DVE\,DCC} = DVEavailbility_{DCC}/DVErequirement_{DCC} \quad \text{(cows) (Eq. 16)}$$

$QDCC_{VEM\ DCC}$	= The quantity of a specific DCC which can be provided with enough energy from the available feed for intake (cows)
$VEMavailability_{DCC}$	= The energy available in the quantity feed available for a DCC in 2018 (VEM/year)
$VEMrequirement_{DCC}$	= The energy intake required for subsistence, grazing, gestation, lactation and/or milk production for a specific dairy cattle category in 2018 (VEM/cow/year)
$QDCC_{VEM\ DCC}$	= The quantity of a specific DCC which can be provided with enough protein from the available feed for intake (cows)
$DVEavailability_{DCC}$	= The protein available in the quantity feed available for a DCC in 2018 (Kg DVE/year)
$DVErequirement_{DCC}$	= The protein intake required for subsistence, growth, gestation, and/or milk production for a specific daiyr cattle category in 2018 in 2018 (Kg DVE/cow/year).

The VEM and DVE Availability

The total VEM and DVE availability in the feed for dairy cattle is calculated with equation 13 and 14 by multiplying the quantity DS (in kg DS) with the VEM or DVE content (in VEM per kg DS and kg DVE per kg DS) per feed category and, subsequently, adding the N embedded in each feed commodity. In scenario A, the quantity DS intake of feed commodity *nx* is equal to the global production of this commodity, in scenario B, the DS intake of commodity *nx* is equal to the European production of this commodity, and, in scenario C, the DS intake of commodity *nx* is equal to the national production of this commodity. **Table 2** contains the total DS intake and in Table 3 contains the VEM-content and DVE-content of the different feed categories for the year 2018.

$$VEMavailbility_{DCC} = Qfeed2_{n1\,DCC} \cdot VEMcont_{n1} + Qfeed2_{n2\,DCC} \cdot VEMcont_{n2} + Qfeed2_{nx\,DCC} \cdot VEMcont_{nx} \quad \text{(VEM/year) (Eq. 17)}$$

$Qfeed2_{nx\ DCC}$	= The total amount of feed of commodity *nx* provided to a specific DCC minus the feeding losses in 2018 (Kg DS/year).
$VEMcont_{nx}$	= The N content of feed commodity *nx* (VEM/Kg DS)

$$DVEavailbility_{DCC} = Qfeed2_{n1\,DCC} \cdot DVEcont_{n1} + Qfeed2_{n2\,DCC} \cdot DVEcont_{n2} + Qfeed2_{nx\,DCC} \cdot DVEcont_{nx} \quad \text{(Kg DVE/year) (Eq. 18)}$$

$DVEcont_{nx}$	= The N content of feed commodity *nx* (Kg DVE/Kg DS)

VEM and DVE Requirement

The VEM and DVE requirement per cow is calculated using equations 19 to 24. The VEM requirement per cow for all DCCs is dependent on the energy need for subsistence and grazing. Additionally, the VEM requirement per cow for YS>1 and MC depends on the energy need for gestation, and, furthermore, the VEM requirement per cow for MC depends on lactation and milk production. The

DVE requirement per cow for all DCCs is dependent on the protein need for subsistence and growth. Additionally, the DVE requirement per cow for YS>1 and MC is dependent on the protein need for gestation, and furthermore, the DVE requirement per cow for MC depends on milk production. The VEM and DVE requirement per cow is equal in the three scenarios utilised in this thesis and is based on data for the year 2018. The equations are retrieved from Duinkerken & Spek (2016). In Table 3 the DVE content and VEM content of feed types is displayed.

The VEM requirement per cow is calculated with the following equations:

$$VEMrequirement_{YS<1} = (VEMsubsist_{YS<1} + VEMgrazing_{YS<1}) \cdot 1{,}02$$ *(VEM/cow/year) (Eq. 19)*

$$VEMrequirement_{YS>1} = (VEMsubsist_{YS>1} + VEMgrazing_{YS>1} + VEMgestation_{YS>1}) \cdot 1{,}02$$ *(VEM/cow/year) (Eq. 20)*

$$VEMrequirement_{MC} = (VEMsubsist_{MC} + VEMgrazing_{MC} + VEMgestation_{MC} + VEMlactation + VEMmilk) \cdot 1{,}02$$ *(VEM/cow/year) (Eq. 21)*

VEMsubsist $_{DCC}$	= The energy required for subsistence of a DCC in 2018 (VEM/cow/year)
VEMgrazing $_{DCC}$	= The energy required for grazing of a DCC in 2018 (VEM/cow/year)
VEMgestation $_{DCC}$	= The energy required for gestation of a MC or YS>1 in 2018 (VEM/cow/year)
VEMlactation $_{DCC}$	= The energy required for youth surcharge, or lactation, of MC in 2018 (VEM/cow/year)
VEMmilk $_{DCC}$	= The energy required for milk production of MC in 2018 (VEM/cow/year)

The DVE requirement per cow is calculated with the following equations:

$$DVErequirement_{YS<1} = (DVEsibsit_{YS<1} + DVEgrowth_{YS<1})$$ *(Kg DVE/cow/year) (Eq. 22)*

$$DVErequirement_{YS>1} = (DVEsubsist_{YS>1} + DVEgrowth_{YS>1} + DVEgestation_{YS>1})$$ *(Kg DVE/cow/year) (Eq. 23)*

$$DVErequirement_{MC} = (DVEsubsist_{MC} + DVEgrowth_{MC} + DVEgestation_{MC} + DVEmilk_{MC})$$ *(Kg DVE/cow/year) (Eq. 24)*

DVEsubsist	= The protein required for subsistence of a DCC in 2018 (Kg DVE/year)
DVEgrowth	= The protein required for growth of a DCC in 2018 (Kg DVE/year)
DVEgestation	= The protein required for gestation of a MC or YS>1 in 2018 (Kg DVE/year)
DVEmilk	= The protein required for milk production in MC in 2018 (Kg DVE/year)

Table 3. *The VEM and DVE content of different feed types fed to the three dairy cattle categories in 2018. YS stands for young stock and includes young stock younger than 1 year and older than 1 year. MC stands for milk cows. The VEM and DVE content is retrieved from personal communication (F. Gort, personal communication, March 3, 2021) and Blok & Spek (2018).*

Feed type:	**VEM content (VEM/kg DS)**	**DVE content (g DVE/kg DS)**
Milk(powder)	120,0	107,0
Singular Feed YS	959,7	86,3
Singular Feed MC	944,8	136,4
Compound Feed YS	940,0	128,7
Compound Feed MC	950,9	132,4

Moisture Rich Feed	1029,6	104,2
Grass and Hay Silage	956,0	69,0
Maize Silage	9530	52,0
Pasture Grass	955,0	87,0

Roughage Production Sub-system

To calculate the size of the flows in the roughage production system for scenario A, B and C, the equations listed below can be utilised.

Nitrogen Balance in the Soil

The main N flows in the roughage production sub-system is the input of N through manure, chemical fertilizer, deposition, BNF, and mineralisation, and the output of N through crop yield, and emissions (See Figure 6). The difference between the input and the output of N to the soil is the soil surplus. The N balance in roughage production is described by equation 25. Equation 26 describes the general equation for the N in products added or subtracted from the soil. The N in products is calculated by multiplying the quantity crop product (in kg) with the N content of the products (in kg N/kg product). To calculate the N application of chemical fertilizer equation 27 is used. The chemical fertilizer application is calculated by subtracting the efficient part of N in manure from the total fertilizer application.

$$Nsoil\ surplus = Nmanure + Nchem + Ndeposition + Nfixation + Nmineralisation - Nyield - Nemissions$$

(Kg N/year) (Eq. 25)

Nsoilsurplus = The soil surplus which is the difference between the N input to the soil and the N output (Kg N/year)

Nmanure = The N applied to the soil in the form of manure in 2018 (Kg N/year)

Nchem = The N applied to the soil in the form of chemical fertilizers in 2018 (Kg N/year)

Ndeposition = The total BNF to the soil in 2018 (Kg N/year)

Nfixation = The total N fixed in the soil in 2018 (Kg N/year)

Nmineralisation = The quantity N available in the soil through the mineralisation of peat soils in 2018 (Kg N/year)

Nyield = The N contained in crop yield in 2018 (Kg N/year)

Nemissions = The total N emitted to the atmosphere resulting from the application of fertilizers in 2018 (Kg N/year)

The general equation for the N in products added or subtracted from the soil is the following:

$$Ncropproduct = Qcropproduct_{nx} \cdot Ncontcropproduct_{nx}$$

(Kg N/year) (Eq. 26)

$Qproduct_{nx\ DCC}$ = The quantity crop product *nx* for a specific DCC in 2018 in 2018 (Kg/year)

$Ncontprod_{nx}$ = The N content of animal product *nx* (Kg N/Kg product)

To calculate the N application of chemical fertilizers on dairy farms the following equation is used:

$$Nchem = Nfertilizer - Nmanure \cdot 0{,}6$$

(Kg N/year) (Eq. 27)

Nfertilizer = The N applied to the soil in the form of fertilizer, including manure and chemical fertilizer in 2018 (Kg N/year)

3.2 Scenarios for circular N flows in Dairy farming

To quantify the impact of more circular N flows on the production in the Dutch dairy farming system, three alternative scenarios were developed for this study as described in the introduction: Scenario A) the conventional Dutch dairy sector in 2018, Scenario B) the elimination of feed imports from outside Europe, and Scenario C) the elimination of feed imports altogether. The scenarios were defined to examine the implications of three different scopes of circularity on the N flows in the Dutch dairy sector. Especially, the impact for the dairy cattle stock, the milk production and the N emissions are of keen interest. These changes in N flows can assist to achieve the reductions in N emissions as described in different policy advice and plans (Ministerie van LNV, 2019b; Remkes et al., 2020), however, at the same time, they can impact socio-economic situation of different actors and impact the cultural values of the Dutch society. Due to the far-stretched impact the scope of CA can have on the dairy farming sector, and the people depending on it, it is important to assess the potential consequences through scenario-building. Scenario-building is a useful tool to govern complex systems. The three scenarios are developed for the year 2018 and are counterfactual scenarios. In counterfactual analysis, a real world is compared with a constructed world with at least one distortion (Gordon & Todorova, 2019). By comparing the real world, in this case the reference situation of the diary sector in 2018, to a (future) world changed by the insertion of the alternate decision, in this case reducing feed imports on different scopes in the dairy sector, the consequences of the change can be traced. This manipulation of the past can be used for, for example, political decision-making (Gordon & Todorova, 2019). Considering the current societal and political debate on N emissions in the dairy sector, and CA as potential solution to tackle the N emissions in the sector, the three scenarios were developed. **Figure 8** represents the three scenarios schematically.

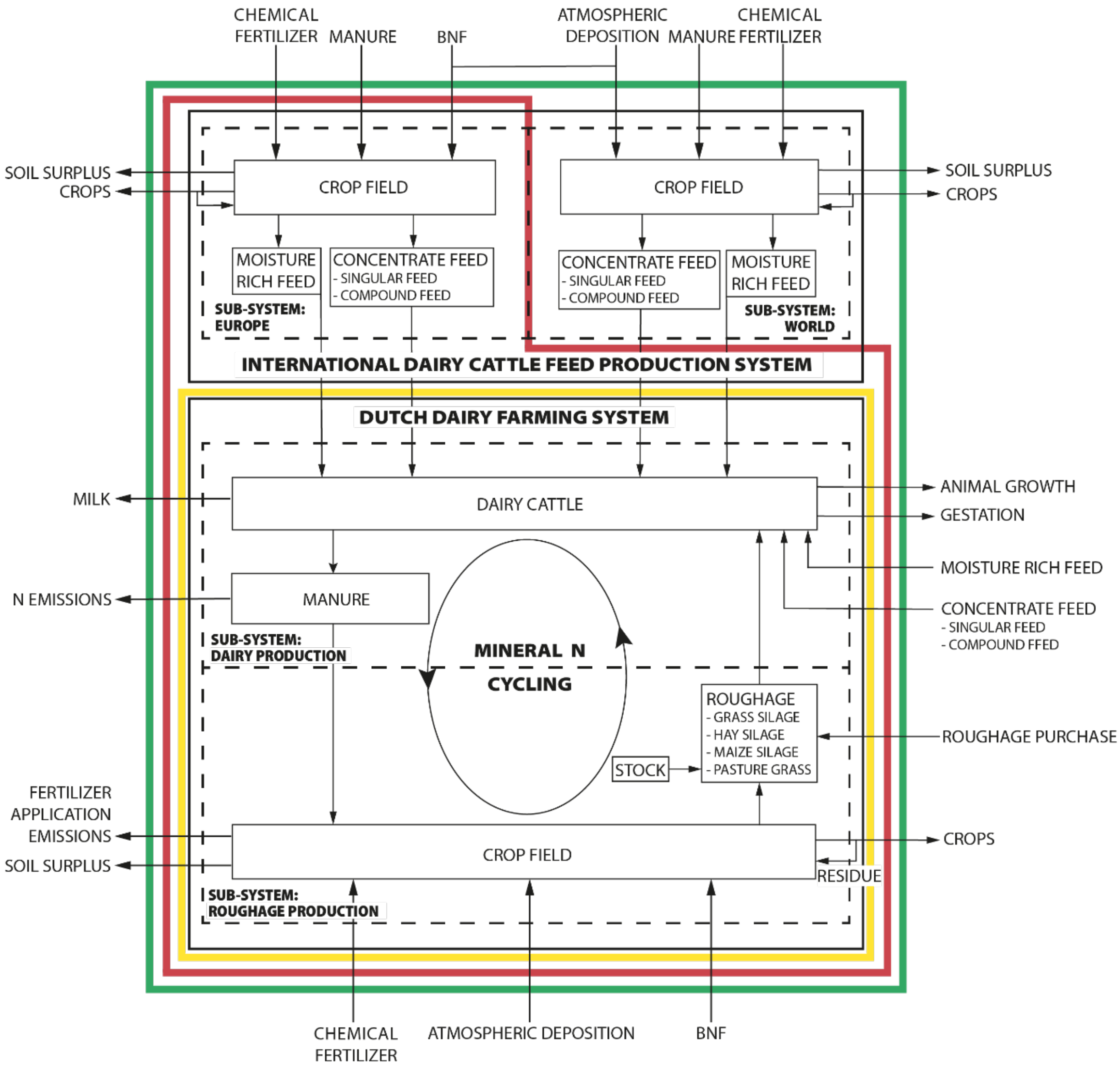

Figure 8. *A schematic representation of the N flows in the three scenarios for the dairy farming system. The green line instigates the N flows of the dairy farming system which are considered in scenario A. In scenario A, the N flows in the reference situation is portrayed. The red line instigates the N flows of the dairy farming system which are considered in scenario B. In scenario B, the N input through feed from outside Europe is eliminated. The orange line instigates the N flows of the dairy farming system which are considered in scenario C. In scenario C, the N input through feed from outside the Netherlands is eliminated.*

3.2.1 Scenario A: The Conventional Situation

In scenario A, the conventional situation in 2018 is portrayed. This reference scenario of 2018 is the situation which is used as the starting point for the comparison of the two alternative scenarios in this thesis. Such a benchmark is important to understand the full scope of the current situation and to correctly evaluate the effects of the proposed changes to this situation (Baranzelli et al., 2015). The performance of the new situations in scenario B and C can be evaluated against this baseline scenario.

3.2.2 Scenario B: The Elimination of Feed Imports Outside Europe

In scenario B, feed imports from outside the European continent are eliminated from the system. Feed imports is the largest N flow entering the Dutch agricultural sector (Compendium voor de Leefomgeving, 2020). These imports are relatively high in N-content (Sander et al., 2016). Therefore, feeding only European produced commodities can distort the balanced cattle diet. As such, the reduction in feed imports can impact the dairy cattle stock size and its total productivity. Besides, the decrease in N input can influence the N losses to the environment within the system.

3.2.3 Scenario C: The Elimination of Feed Imports

In scenario C, feed imports for the Dutch dairy farming sector are eliminated altogether. The only feed that is fed to dairy cattle is, thus, produced on Dutch arable land or originates from by-products of the Dutch processing industry. This scenario eliminates the largest import flow of N into the Dutch agricultural system. Changes in the N flows can influence the productivity of the dairy farming sector, as well as the N losses to the environment.

4. Results

This chapter presents the results for the different scenarios as calculated in the model described in *Chapter 3*. First, the changes in quantity dairy cattle stock and milk production based on the feed commodities, quantity and origin is discussed. Second, an overview of N flows in the Dutch dairy farming system for the three scenarios are portrayed by means of Sankey Diagrams. The changes in N emissions and soil surplus in the different scenarios is discussed subsequently.

4.1 Dairy Cattle Stock and Milk Production

The quantity cattle stock and milk production depend on the VEM and DVE availability in feed. The VEM and DVE availability in feed differ in the different scenarios based on the origin of the feed types. The origin of the feed types in turn depends on the feed products of which the feed types consist, and their origin. Therefore, this section starts with a description of the feed category, quantity N and origin of the feed commodities fed to dairy cattle in 2018. The origin of the feed commodities does not only determine the feed available in the different scenarios, but also shows the embeddedness of the Dutch dairy sector in international trade. The section continues with the description of the VEM and DVE requirement per cow, the VEM and DVE availability in the different scenarios, and the resulting quantity dairy cattle stock and milk production.

4.1.1 Feed Products, Quantity and Origin

In 2018, the total feed intake of the Dutch dairy cattle accounted for 13,7 million ton, of which 9,75-million-ton roughage (71,4%), 2,95-million-ton compound feed (21,6%), 0,54-million-ton moisture rich feed (3,9%), and 0,42-million-ton singular feed. The intake of feed types differs between the dairy cattle categories. Milk cows are fed with the largest share of concentrate feed, accounting for 32% in comparison with 23% for young stock younger than 1 and 3% for young stock older than 1. The rest of the diet consists of roughage, and for milk cows of moisture rich feed. Especially, grass and hay silage have the largest share in the diet of young stock older than 1 year with 70%, and accounts for 62% of the diet of young stock younger than 1 year, and 42% of the diet of milk cows.

The feed types, roughage, concentrate and moisture rich feed, consist of feed commodities which are produced in a certain region in the world. All roughage fed to dairy cattle is produced in the Netherlands. Of the moisture rich feed, 81% is produced in the Netherlands, 18% in the rest of Europe, and 1% in the rest of the world. Compound feed is for 12% produced in the Netherlands, 45% in the rest of Europe, and 43% in the rest of the world. And singular feed is for 42% produced in the Netherlands, 46% in the rest of Europe, and 12% in the rest of the world.

The total N embedded in feed for Dutch dairy cattle in 2018, accounted for 359 million kg. The average N content per kg product is the highest for non-European produced feed with 20%, compared to 18% of European produced feed, and 16% for feed produced in the Netherlands. The ratio of the quantities produced feed per region (Netherlands: 78%, Europe: 12%, and World: 10%) differs from the ratio of the N produced in feed per region (Netherlands: 75% N, Europe 13% N, and World: 12% N). Table 4 contains the feed types, quantity N and origin of the feed commodities fed to dairy cattle in 2018.

***Table 4**. The origin of the feed commodities fed to dairy cattle in 2018 in percentages. The feed category to which the feed commodities belong is indicated with a C for compound feed, S for singular feed, M for moisture rich feed, and R for roughage. The feed commodities are divided in three different origins in which the feed is produced: Dutch origin, European origin, and world origin. European origin contains all countries on the continent Europe, excluding the Netherlands. World origin contains all countries in the world, excluding the countries on the European continent. The data is based on detailed trade data from Statline, FAOSTAT, EUROSTAT and Nevedi (CBS StatLine, 2021; Eurostat, 2021; FAOSTAT, 2021; Nevedi, 2018).*

Feed Commodity	Feed Category	Quantity N (Kg N / year)	Dutch Origin (%)	European Origin (%)	World Origin (%)
Barley	C	2.183.004	10	90	0
Beet, pulp	M	2.659.498	68	32	0
Beet, pulp	S	1.475.291	68	32	0
Beet & cane, pulp	C	577.799	68	32	0
Brewer's grains	M	4.856.672	100	0	0
Cane, molasses	C	854.041	10	6	84
Chicory, press pulp	M	116.651	100	0	0
Citrus, pulp	C	78.856	0	0	100
Citrus, pulp	S	81.744	0	0	100
Drinks and other	M	12.266	100	0	0
Grass, pasture	R	50.114.245	100	0	0
Grass and hay, silage	R	164.576.658	100	0	0
Lupin	C	1.532.650	2	13	85
Maize	C	4.774.340	2	80	18
Maize	S	525.961	2	80	18
Maize, fresh gluten feed	M	1.907.681	30	70	0
Maize, DDGS	C	3.874.791	39	61	0
Maize, distillers	C	13.307.368	39	61	0
Maize, gluten	C	1.873.014	30	70	0
Maize, gluten feed	S	1.667.937	30	70	0
Maize, green/silage	R	28.524.438	100	0	0
Milk, dried	S	459.899	100	0	0
Palm, kernel	C	12.027.082	0	0	100
Palm, oil	C	38.834	0	0	100
Palm, oil fatty acids	C	29.225	0	0	100
Peas	C	3.888.262	14	78	9
Peas, other	M	176.288	100	0	0
Potato, cuts	M	302.682	100	0	0
Potato, other	M	64.287	100	0	0
Potato, peelings	M	171.814	100	0	0
Potato, pulp product	M	606.660	100	0	0
Potato, starch	M	52.364	100	0	0
Vegetable, fruit, juice products from processing	M	137.575	100	0	0
Rapeseed, flour	C	275.017	4	97	0
Rapeseed, meal	C	4.006.569	4	97	0
Rapeseed, meal	S	2.177.025	4	97	0
Rapeseed, pellet	C	1.038.928	4	97	0
Rye	C	966.355	6	94	0
Soy, grain	C	3.758.553	0	5	95
Soy, meal	C	13.095.239	0	5	95
Soy, meal	S	5.423.808	0	5	95
Soy, products	M	113.013	0	5	95
Soy, skin	C	4.929.029	0	5	95
Sunflower, meal	C	1.043.311	14	57	30
Triticale	C	4.171.792	6	94	0
Vinasse	C	3.101.777	10	6	84
Wheat	C	1.091.845	18	82	0
Wheat, crushed	S	1.480.349	18	82	0
Wheat, other	M	99.684	48	52	0
Wheat, yeast	C	3.417.522	48	52	0
Wheat, yeast concentrate	M	2.376.403	100	0	0

Figure 9 visualises the countries from which feed is imported for the Dutch dairy cattle in percentages of the total feed imports. The largest share in feed products produced in the Netherlands besides roughage, are co-products from the sugar, beer, and alcohol production (beet pulp, brewer's grains, and maize distillers). Within Europe, excluding Dutch production, Germany (40%), France (21%), Belgium (16%), and Ukraine (13%) together produce about 90% of the feed imported for Dutch dairy cattle. The largest import of N in products from outside Europe are soy and palm oil. Other products imported from outside Europe are pulp from citrus and sugar cane, sunflower meal, and maize products. From Europe, the largest feed imports are different types of grains, among which, rye, maize, and barley. Excluding European production, the largest part of dairy cattle feed is imported from Asia (43%), North America (30%) and South America (23%). Especially, Indonesia (34%), the United States of America (29%), and Brazil (19%) produce a large share of the non-European feed for dairy cattle in the Netherlands.

Figure 9. *The origin of feed imports for Dutch dairy cattle in 2018 in percentages of total quantity feed (kg) import for dairy. The left image portrays the feed imports from outside the Netherlands for the entire world. The right image portrays the feed imports from outside the Netherlands from Europe. The Figure is created with Datawrapper (2021).*

4.1.2 Quantity Livestock and Milk Production

The VEM requirement of dairy cattle is determined with the methodology in section 3.2 and set on 6.817.130 VEM per cow per year for milk cows, 1.804.135 VEM per cow per year for young stock younger than 1 year, and 2.493.896 VEM per cow per year for young stock older than 1 year. The VEM requirement for milk cows is partly based on a milk production of 8.848 kg per cow per year. The VEM uptake is two percent higher than the calculated VEM requirement since the VEM coverage is assumed to be 102% (van Dijk et al., 2020). The DVE requirement of dairy cattle is determined on 560.072 g DVE per cow per year for milk cattle, 123.953 g DVE per cow per year for young stock younger than 1 year, and on 195.625 g DVE per cow per year for young stock older than 1 year. The DVE requirement of milk cows is based on milk production of 24,24 kg per day per cow with an average protein content of 3,56% in 2018 (CBS StatLine, 2021).

In scenario B, the number of milk cows decreased with 13%, while the feed imports only decreased with 10%. And in scenario C, the feed imports decreased by 22%, while the number of milk cows decreased by 31%. The differences in import reduction and cattle stock reductions are related to the changes in composition of the feed and the resulting changes in VEM and DVE availability. According to van Liefferinge (2011), farmers tend to slightly feed their cattle above the DVE requirement standards because of the negative affect a deficiency can have on the milk production. In scenario A, the dairy cattle are fed between 1% and 3% above the DVE requirement. Except for young stock older than 1 year in scenario B, the dairy cattle in scenario B and C are not fed more than the actual DVE requirement. The milk production of milk cows decreases with 13% in scenario B, and 31% in scenario C in comparison to scenario A. Table 5 shows the VEM availability, DVE availability, livestock quantity and milk production in the three scenarios utilised in this thesis.

The RE content per kg DS provided to dairy cattle in 2018 changes in the different scenarios. In scenario A, the RE intake for milk cows is 164 RE per kg DS, in scenario B, the RE intake for milk cows is 158 RE per kg DS, and, in scenario C, the RE intake for milk cows is 155 RE per kg DS.

Table 5. *The VEM and DVE availability, livestock quantity and milk production in the three scenarios. The VEM and DVE availability in the available feed for a specific dairy cattle category determined the quantity of livestock in the three scenarios in 2018. Based on the quantity milk cows, the total milk production is determined. The percentages show the decrease (-) or increase (+) in livestock quantity and milk production in comparison to scenario A.*

	Scenario A	**Scenario B**	**Scenario C**
VEM Availability (VEM/year)			
Milk cows	11.069.286.790.634	9.875.068.349.969 (-11%)	8.397.823.955.473 (-24%)
Young stock < 1 year	788.654.782.513	736.955.151.841 (-7%)	686.003.811.743 (-13%)
Young stock > 1 year	1.320.127.335.051	1.300.277.947.988 (-2%)	1.281.209.321.757 (-3%)
DVE Availability (Kg DVE / year)			
Milk cows	908.643.222	774.347.399 (-16%)	611.850.210 (-34%)
Young stock < 1 year	54.701.800	48.993.000 (-10%)	43.545.856 (-20%)
Young stock > 1 year	102.952.078	100.769.303 (-2%)	98.711.171 (-4%)
Livestock Quantity (Cows)	**2.541.000**	**2.292.984 (-10%)**	**1.947.424 (-23%)**
Milk cows	1.591.000	1.382.585 (-13%)	1.092.449 (-31%)
Young stock < 1 year	429.000	395.255 (-8%)	351.310 (-18%)
Young stock > 1 year	521.000	515.144 (-1%)	503.665 (-3%)
Milk Production (Kg milk / year)	**14.076.449.820**	**12.232.488.405 (-13%)**	**9.665.494.595 (-31%)**

4.2. Nitrogen Flows in the Dutch Dairy Farming Sector

This section provides an overview of N flows in the Dutch dairy farming sector for the three scenarios. The section starts with a visualisation of the N flows in the three scenarios and compares the changes of N resulting from the elimination of feed imports. The section proceeds by a quantification of the N losses in terms of soil surplus and emissions.

4.2.1. Visualisation of Nitrogen Flows

The Sankey diagrams in Figure 10, Figure 11 and Figure 12 visualise how the N in resources are converted into valuable products or lost as waste. The processes are shown in white squares and have an inflow and outflow of N. The thickness of the arrow portrays the size of the N flows. The N flows with a downward direction are part of the dairy production system and the N flows with an upward direction are part of the crop production system. The processes with only an inflow and no outflow connected to it are exported from the system, and the processes with only an outflow and no inflow connected to it are imported into the system. The N emissions and soil surplus are portrayed in orange. The numbers in the dairy cattle processes show the number of dairy cattle in the system. The remaining numbers show the quantity of N in a specific inflow or outflow of a process in kg. The N flows through the system provide insight into the size of the flows and efficiency of the dairy farming system under the different scenarios. Inefficiencies in the system highlight leverage points to make the system more circular.

Scenario A, which simulates the N flows in the dairy farming sector in 2018, is portrayed in Figure 10. The total input of N embedded in feed for dairy cattle is 372.360.680 kg N. The total export of N from dairy production embedded in milk, N manure emissions, and manure exports is 171.258.245 kg N. The total input of N to the soil of dairy farms is 337.776.087 kg N. The total export of N from crop production embedded in N application emissions, soil surplus and crop exports are 132.328.020 kg N. Although a large part of N in the dairy farming system is recycled through the fertilization of land, there is also import and export of N in the system. The import is portrayed in vertical direction and the export in horizontal direction. The largest import into the system is related to dairy feed and agricultural input. Especially feed (118.490.577 kg N) and chemical fertilizers (102.221.756 kg N) account for a large share of imports into the system. Besides feed and chemical fertilizers, N enters the system through mineralisation, BNF and atmospheric deposition. N is exported from the dairy farming system through fixation of N in growth, gestation, and milk, sales of plant products and manure, and losses of N through N emissions and soil surplus. Within the system there are several 'return flows' which returns extracted N from dairy production. The largest return flow is the flow of N through roughage production and stock. Besides roughage, N returns to the system through deposition of volatilized N.

Scenario B, which simulates N flows in the dairy farming sector in 2018 without imports from outside Europe, is portrayed in Figure 11. The total input of N embedded in feed for dairy cattle is 325.496.652 kg N, which is 13% less in comparison to scenario A. The total export of N from dairy production embedded in milk, growth, gestation, N emissions, and manure exports is 124.394.218 kg N, which is 27% less in comparison to scenario A. The input of N in crop production and the export of N from crop production is equal to scenario A. The largest changes in the N flows in the system compared to the N flows in scenario A are feed imports and export or processing of manure. In scenario A, there was an import of N embedded in compound feed of 93.984.668, in moisture rich feed of 14.063.167, and in singular feed of 10.442.741 kg N. These imports changed to 51.947.991 kg N imported through compound feed, 13.928.821 kg N through moisture rich feed, and 5.771.999 kg N through singular feed in scenario B. For compound and singular feed this change in imports of N accounts to a 45% decrease in scenario B compared to scenario A. Manure exports from the system changed from 55.449.157 kg N in scenario A to 23.837.580 kg N in scenario B. The N emissions from dairy cattle also decreased in scenario B compared to scenario A. In scenario A, the N emissions from dairy cattle is 29.102.907 kg N, while in scenario B, the N emissions from dairy cattle is 24.703.776 kg N.

Scenario C, which simulates the N flows in the dairy farming sector in 2018 without imports from outside the Netherlands, is portrayed in Figure 12. The total input of N embedded in feed for dairy cattle is 278.512.615 kg N, which is 25% less in comparison to scenario A. The total export of N from dairy production embedded in milk, growth, gestation, N emissions, and manure exports is 77.410.181 kg N, which is 55% less in comparison to scenario A. The input of N in crop production and the export of N from crop production is equal to scenario A. The largest changes in the N flows in the system compared to the N flows in scenario A are again feed imports, manure exports and N emissions from dairy cattle. The N imports embedded in feed in scenario C are 11.755.632 kg N through compound feed, 11.602.960 kg N through moisture rich feed, and 1.306.181 kg N through singular feed. The total change in feed imports in scenario C accounts to a decrease of 79% compared to scenario A and 66% compared to scenario B. Manure exports from the system is equal to zero in scenario C. The N emissions from dairy cattle is 20.946.684 kg N in scenario C, which is a decrease of 28% compared to scenario A, and 15% compared to scenario B.

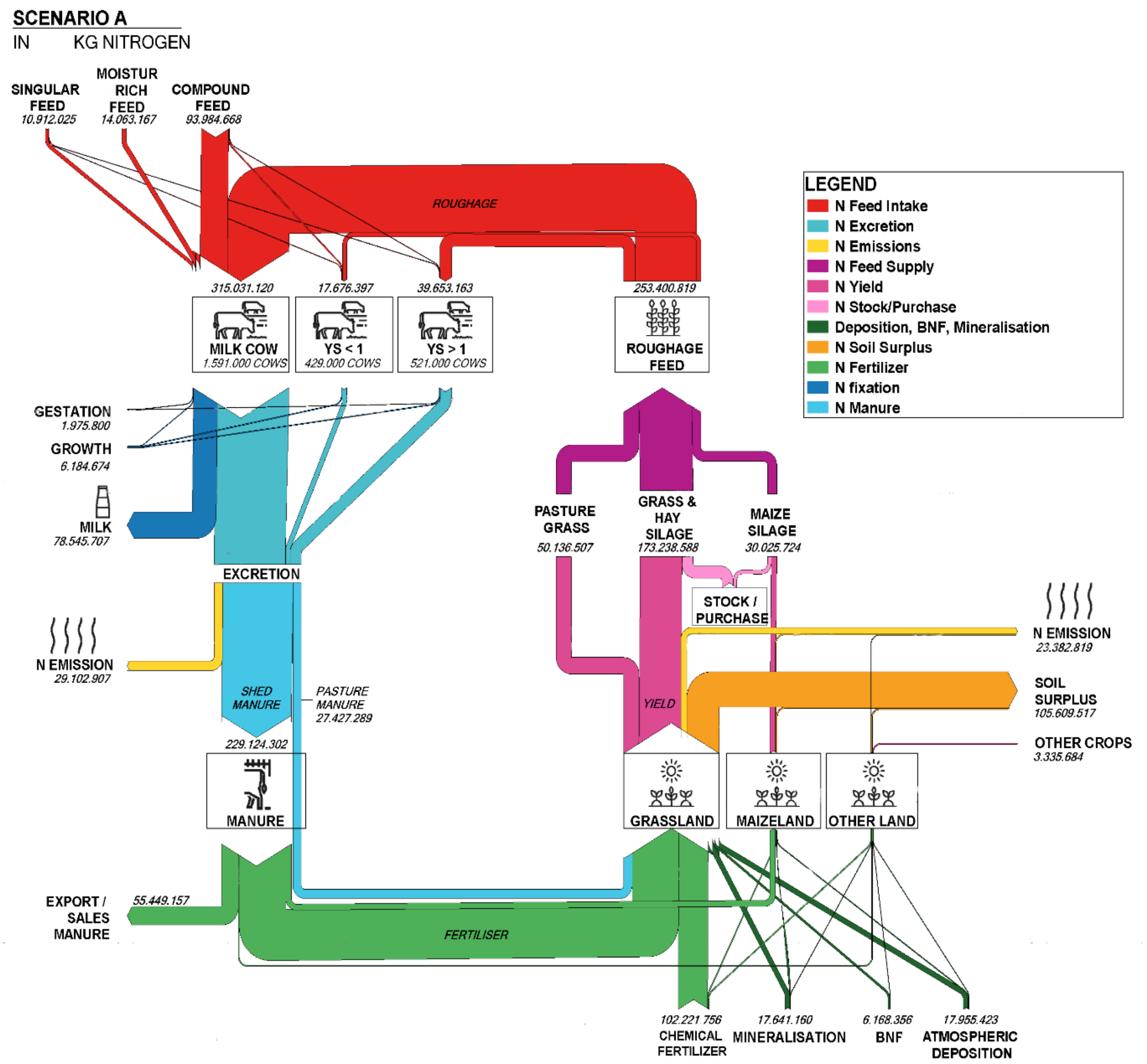

__Figure 10__. Representation, in 2018, of the N fluxes across the dairy farming system in scenario A expressed in ton kg N. Squares represent the processes occurring, and the width of the arrows are proportional to the intensity of the fluxes involved in these processes. The downward arrows are part of the dairy production system, and the upward flows are part of the crop production system. Export from and import into the system is portrayed by processes with only one arrow connected to it. Horizontal flows represent exports from the system. The largest import into the system is from N embedded in feed and chemical fertilizer. The largest export from the system is through N emissions, soil surplus, and manure and milk export.

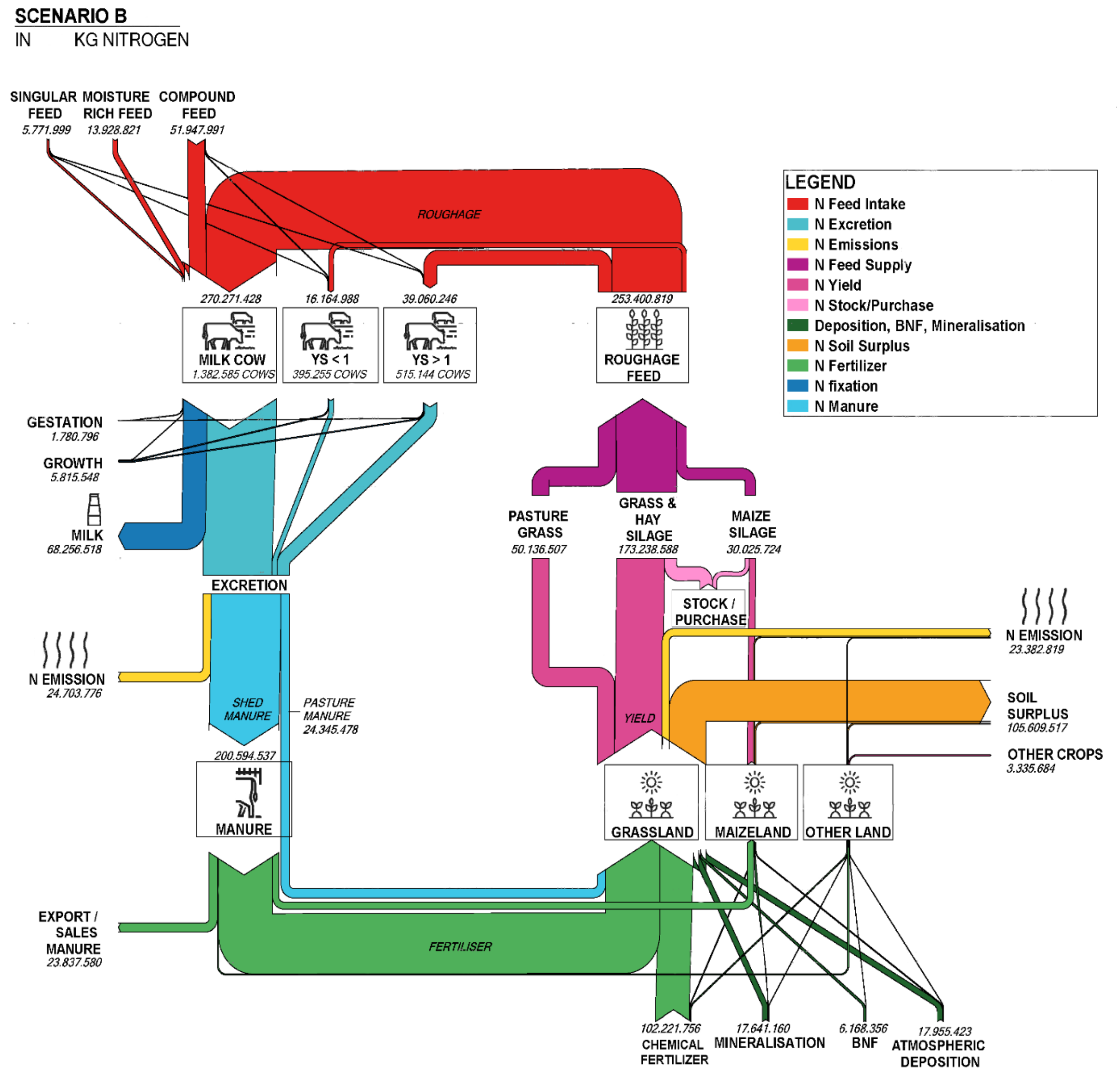

Figure 11. *Representation, in 2018, of the N fluxes across the dairy farming system in scenario B expressed in ton kg N. In scenario B, the imports of feed from outside Europe are eliminated, which causes a decrease in the N imported through feed in comparison to scenario A. The decreased N input leads to a decrease of N fixed in milk and excretion. As a result, the manure production and N emissions decrease.*

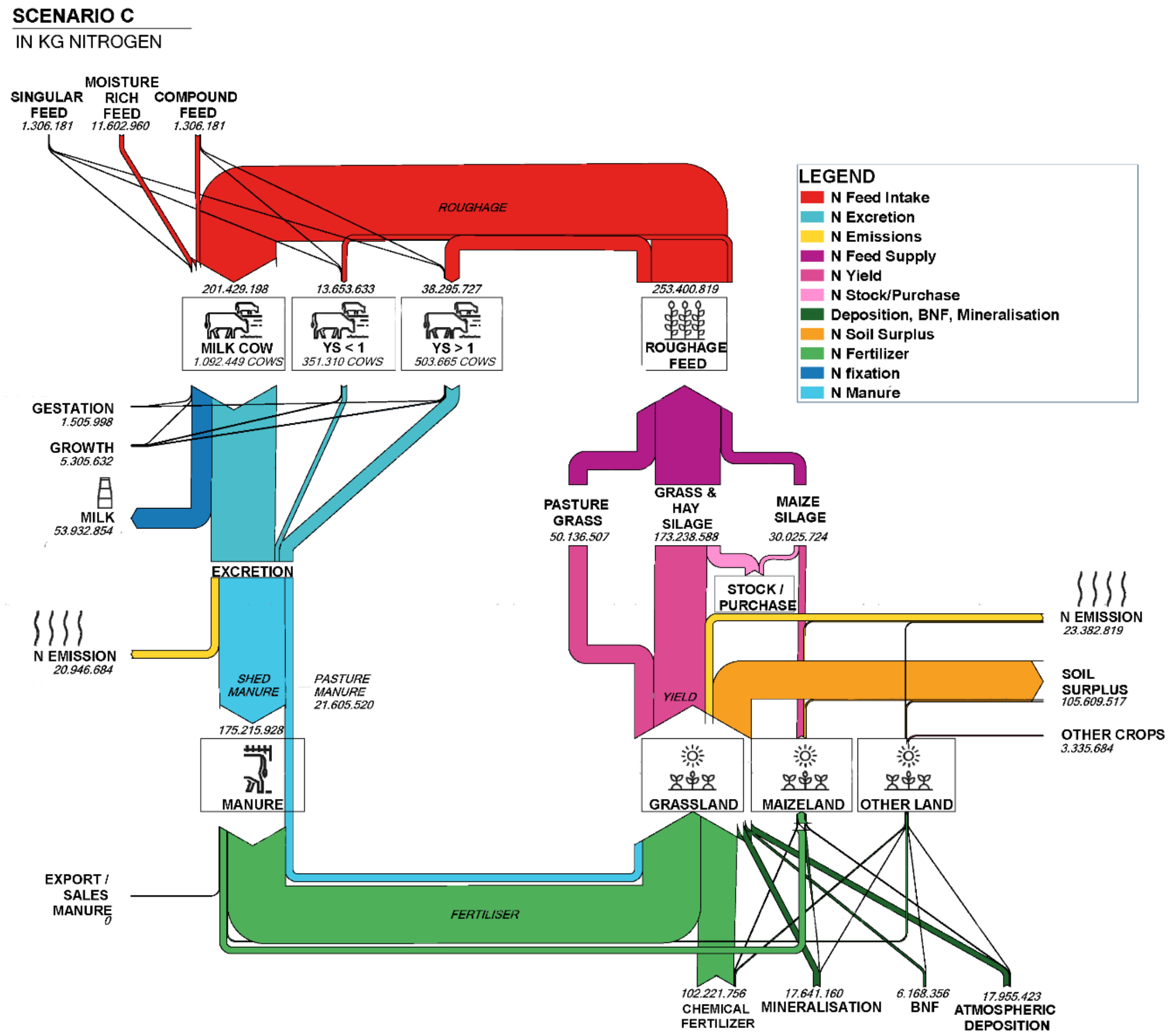

__Figure 12.__ Representation, in 2018, of the N fluxes across the dairy farming system in scenario C expressed in ton kg N. In scenario C, the imports of feed from outside Europe are eliminated, which causes a decrease in the N imported through feed in comparison to scenario A and B. The decreased N input leads to a decrease of N fixed in milk and excretion. As a result, the manure production and N emissions decrease.

4.2.2. Nitrogen Emissions in the Scenarios

The total N emissions in the scenarios change with the reduction in imports of feed in the dairy farming system (See Table 6). The total N emissions decrease with 8% in scenario B, and 16% in scenario C. This reduction in N emissions is not proportionate to the decrease in dairy cattle since the fertilizer application emissions of N has remained equal in the three scenarios. Furthermore, the N emissions are dependent on the feed composition and as this composition changes in the scenarios, the decreases do not entirely correspond to the decreases in cattle stock. The soil surplus in the three scenarios remains equal and accounts for 105.609.517 kg N.

Table 6. *The N-emissions from manure excretion, storage, and application of the dairy farming system in scenario A, B and C. In scenario A, the conventional situation in 2018 is simulated. In scenario B, the feed imports from outside Europe are eliminated. And, in scenario C, the feed imports from outside the Netherlands are eliminated. The percentages show the differences in N emissions in comparison to scenario A.*

	Scenario A	Scenario B	Scenario C
Total N emissions (kg/year)	**52.485.726**	**48.086.595 (-8%)**	**44.329.503 (-16%)**
NH_3 emissions shed (kg/year)			
Milk cows	19.120.659	15.709.202 (-18%)	12.956.520 (-32%)
Young stock < 1 year	867.806	807.486 (-7%)	727.374 (-16%)
Young stock > 1 year	2.590.406	2.576.026 (-1%)	2.513.807 (-3%)
Other N emissions shed (kg/year)			
Milk cows	5.087.788	4.277.126 (-16%)	3.514.264 (-31%)
Young stock < 1 year	315.729	288.334 (-9%)	262.585 (-17%)
Young stock > 1 year	665.173	652.618 (-2%)	638.901 (-4%)
N emissions external storage (kg/year)			
Milk cows	375.565	316.455 (-16%)	259.914 (-31%)
Young stock < 1 year	25.679	23.451 (-9%)	21.357 (-17%)
Young stock > 1 year	54.101	53.080 (-2%)	51.964 (-4%)
N emissions fertiliser application (kg/year)	**23.382.819**	**23.382.819 (-0%)**	**23.382.819 (-0%)**

5.Discussion

In this chapter, first, a summary of the results as described in *Chapter 4* and their relation to literature and policy documents is provided. Second, the implications of the results for policies are discussed, including the potential points for intervention. Third, the limitations and suggestions for further research are given.

5.1 Summary of Results Embedded in Literature

This study has provided a quantification of N cycling in the Dutch dairy sector and how the availability of N for recycling may change under different scopes of CA. It is clear that the Netherlands imports large quantities of N embedded in feed products, for the largest part in the form of compound feed. These large imports of N embedded in feed, cause the Dutch dairy sector to be much larger than based on national produce only. The N in (imported) feed is converted to animal products and, since cattle only convert 21% to 38% of the nutrients to animal products (Mijnrantsoenwijzer.nl, 2014), there is a large concentration of N in excretion leading to a nutrient concentration loss to the environment. The resulting N emissions precipitate on the soil through deposition and, as such, cause environmental degradation and political crisis in the Netherlands and neighbouring countries (de Wolf et al., 2019; Dolman et al., 2019).

The results show a reduction of N embedded in feed imports of 12% in scenario B, and 25% in scenario C compared to the reference scenario for 2018. This is in accordance with claims from the Dutch animal feed industry association (Nevedi) (*Nederlandse Diervoedersector Loopt Voorop in Gebruik Duurzame Soja*, 2021), which states a national production of 75% of the feed provided to cattle. The reduction in feed imports will have immediate effects on the dairy cattle stock and the dairy production. The number of dairy cattle decrease with 10% in a situation without imports from outside Europe and 23% in a situation without imports altogether in comparison to the reference situation in 2018. The milk production even decreases with 13% without imports from outside Europe and 31% without imports from outside the Netherlands, consistent with the decrease in the number of milk cows. The decrease in the number of milk cows in a situation without imports, scenario C, is comparable to estimations in literature of a decrease of 30% to 35% (Silvis et al., 2021) and 11% to 38% (Terluin et al., 2013). However, Terluin et al. (2013) and Silvis et al. (2021) estimate a larger decrease of milk production with 40% and 35%. This difference might be related to an extra decrease in milk production of 5% to 10% compared to the decrease in milk cows due to a lower protein provision in feed to dairy cattle (Silvis et al., 2021).

The decrease in dairy cattle stock has direct effects on the excretion of dairy cattle. The results show a total excretion of dairy cattle of 285,7 million kg N per year in the reference scenario. This result is comparable to the total excretion provided for by CBS StatLine of 289,9 million kg N per year. Of the excreted manure, 22% is exported from the dairy farm in the reference scenario. Since dairy farms are spread across the Netherlands, and dairy manure has a favourable composition for direct application on agricultural land, most of the manure exported from the dairy farming system is used on the agricultural land of other farming sectors in the region (J. Roefs, personal communication, April 14, 2021). The export of 22% of the manure meets the requirements for farm-farm transport, in which a maximum of 25% of the manure produced on a dairy farm is transferred to another farm while at least 75% is applied on own land (*Vervoeren Met Vrijstelling* , 2021).

The results show that a reduction in feed imports will have immediate positive effects in terms of N emissions to the environment. In a situation without feed imports from outside Europe, the N emissions from manure in shed and external storage, already decrease with 15% and with the elimination of feed imports altogether, these emissions decrease with 28%. This decrease of 15% is in compliance with comparable studies for the entire agricultural sector which quantified a 15% decrease in N losses (Bremmer et al., 2021). The NH_3 emissions in the shed and storage accounted for 23,0 million kg N per year, fertilizer application emissions accounted for 23,4 kg N per year, and grazing emissions accounted for 1,0 kg N per year. The total NH_3 emissions calculated differ with 6,9 million kg N from the total NH_3 emissions provided in Remkes et al. (2020) of 53,8 million kg N in 2018. This difference might be related to emissions related to manure processing and manure application on farmland of other agricultural sectors than dairy farming (Reijs et al., 2021) which is not included in the dairy farming system in this thesis. The results show that a decrease in N imports through feed, result in a decrease in NH_3 emissions. Since NH_3 emissions affect soil and surface water through eutrophication and nitrification and affect nature sensitive to N (Remkes et al., 2020), the decrease in NH_3 emissions has a positive effect on the environment.

5.1.1 Feed intake, Dairy Cattle Stock and Milk Production

In the Dutch policies the National Protein Strategy (2020) and the Circular Agriculture (2019), the target to decline the feed imports from outside Europe is emphasized (Ministerie van LNV, 2019a, 2020). The rationale behind this target is the objective to increase the self-sufficiency of the Netherlands and the EU to lessen the dependence on third countries and increase sustainability. To arrive at this target, both policies endeavour an increase in the production of European alternative protein feed crops, such as legumes, insects, and an increase in the use of co-products (Ministerie van LNV, 2019b, 2020). The increase in European protein-rich feed production fits the strategy for CA on a European scope and could potentially replace all Dutch feed imports from outside Europe. However, the Dutch feed manufacturing industry has annotated that they have not yet found alternative protein-sources for, for example soy, with the same nutritional value, price-quality ration, and environmental impact (Adrichem, 2021). Furthermore, the Dutch feed industry warns that if Europe would stop importing the protein-rich soy and palm products, the control and certification on these products by the EU could disappear, annulling past investments and sustainability improvements (Adrichem, 2021). Hence, several Dutch policies correspond to the European scope of circularity, but the impact of Dutch policies on countries abroad should be taken into consideration as well.

The size of the cattle stock is one of the most heated subjects in the debate about CA (Ploegmakers et al., 2020). Although the policy for CA of the Ministry of LNV does not include a vision for the size of the cattle stock (Ministerie van LNV, 2018, 2019b), many politicians and action groups call for a reduction of the cattle stock of 50% to 75% considering this decreases the N emissions with the same share (Sikkema, 2019). Critics, however, stress that only a decrease in the cattle stock, and accordingly the dairy production, might be counterproductive. A reduction in Dutch production of milk without a reduction in the demand for dairy products could cause unintended spill-over effects, displacing the environmental impacts over the Dutch border (Berkhout & de Puister, 2021; *WUR: Verkleining Veestapel Verplaatst Het Milieuprobleem*, 2021). Furthermore, the results show that a decrease in milk cattle of 31%, the total N emissions only decrease with 16% unless other measures are taken simultaneously to decrease N application emissions as well. Thus, the cutback in cattle stock shrinks the total excretion and emission in the dairy farming system, however, merely focusing on dairy cattle quantities might not reach the intended goals.

Dairy farmers are affected by the implementation of CA on different scopes of circularity. Currently, the average of milk cows per farm is 94 per farm, but the results show that with the reduction in feed imports either this amount decreases to 82 milk cows per farm in scenario B or 64 milk cows per farm in scenario C, or the number of farms reduces from 16.960 farms 14.738 farms in scenario B or to 11.645 farms in scenario C (CBS StatLine, 2021). Considering that in 2018 a milk cow produced 8848 kg milk per year on average (van Bruggen & Gosseling, 2019b) and 37,64 Euro per 100 kg milk is received in 2018 (*Dutch FADN, Agriculture*, 2021), this could lead to a reduction of income between 39.964,65 Euro to 99.911,62 Euro per farm. According to de Wit & van Veluw (2017) a reduction in dairy cattle stock of 27%, comparable to scenario C, can lead to a loss of 1.300 million Euro for dairy farming and dairy processing companies, and 4.300 million Euro for the entire dairy complex. These losses to dairy farmers could be compensated, or sustainable practices encouraged, by for example the use of eco-schemes (Willem Erisman & Anne van Doorn, 2018). Thus, although the results show that a reduction in dairy production does not affect the Dutch consumption of dairy, it does affect the role of the Netherlands in global trade, and the social and economic situation of farmers.

It is clear from the results, that a reduction in feed imports decreases the production of milk. This reduction influences the export of dairy to the European and international market. In 2018, the Netherlands exported dairy products with a worth 7,7 billion Euro (Jongeneel, 2020). A decrease of the same share as the stock reduction in the results of 13% in scenario B or 30% in scenario C could, therefore, amount to a decrease of 1 to 2,3 billion Euro for the sector. This would result in the Netherlands decreasing in rank from the fifth largest dairy exporter in the world in 2018 (ZuivelNL, 2019a), to sixth or seventh place**.** Still, since around 70% of dairy products produced in the Netherlands is exported (ZuivelNL, 2019a), even with reduced and no feed imports from outside the Netherlands, the Netherlands can still export 57% in Scenario B and 40% in scenario C of the dairy produced. Thus, all scopes of circularity discussed in this research do not directly affect the Dutch consumption of dairy products.

On the other hand, a decrease in production without a decrease in demand might cause spill-over effects of the environmental impact of the sector (Berkhout & de Puister, 2021; *WUR: Verkleining Veestapel Verplaatst Het Milieuprobleem*, 2021). The Nationale Eiwitstrategie (2020) and the Realisatieplan Visie LNV: Op Weg Met Nieuw Perspectief (2019) both include a vision on the consumption side of Dutch agriculture. A decrease in production without a decrease in demand might cause spill-over effects of the environmental impact of the sector (Berkhout & de Puister, 2021; *WUR: Verkleining Veestapel Verplaatst Het Milieuprobleem*, 2021). In 2016, dairy was the second most wasted product after bread with 6,8 kg per person per year, accounting for 8,3% of the dairy bought per person in 2016. Only an elimination of milk wasted down the drain of 10,2 Litre per person per year in 2016 in the Netherlands (Stichting Voedingscentrum Nederland, 2017), could lead to a reduction in production of 1,8% and thus a reduction in N emissions, from manure in the shed and storage, with the same share. A global reduction in dairy waste could even lead to a larger reduction in production and N emissions. Another way in which waste of dairy can be minimised is by recycling the N in human excreta back into the dairy production system (de Wolf et al., 2019; Ministerie van LNV, 2019b). To decrease N emissions of the dairy sector, it is important that consumption is decrease simultaneously otherwise N production might spill-over to other areas. Policy measures related to dairy production should thus go along with policy measures related to dairy consumption.

5.1.1 Nitrogen Flows in the Dutch Dairy Farming Sector

The N emissions of dairy cattle depend on the feed intake and composition. The results show that the decreased intake of N embedded in compound and singular feed results in a lower N excretion. Compound and singular feed have a relatively higher RE content per kilogram of feed in comparison to roughage and moisture rich feed, whereas the decrease in protein-rich feed intake results in a lower N excretion. This follows, for example, Plomp & Migchels (2021) where the relatively low protein-rich feed intake of organic dairy cattle compared to conventional dairy cattle, results in lower N excretion. The results demonstrate that with the reduced feed imports, the RE content of DS decreases from 164 g RE per DS in the conventional scenario to 155 g RE per DS in the national scenario. The optimal value of the RE content of DS for dairy cattle is between 150 and 155 g RE per DS (Erisman & Verhoeven, 2019; ten Have, 2020; Verhoeven & Smale, 2014). The reductions in compound and singular feed are in line with several Dutch policies related to N, such as the Program Approach to Nitrogen (PAS), the Water Framework Directive (*kaderrichtlijn water*), and policies related to climate and biodiversity (Erisman & Verhoeven, 2019). Currently, the Dutch government is funding the collaboration Koeien & Kansen to test the feasibility of an average RE content of 155 g RE/DS for the purpose of policymaking (de Haan, 2020). In this manner, the decrease in feed imports as shown in the results can contribute to a lower RE content and a lower N excretion of dairy cattle.

The results show that with a decrease of feed imports, the manure production decreases and therewith, the export of manure from dairy farming system decreases. Most of the manure produced by dairy cattle is used on the land of dairy farms. This is possible since dairy farms include a large share of agricultural land in the Netherlands and often receive the exceptional position to fertilize their grassland more than the European application standard (derogation) (Gies et al., 2017). Still, there is a manure surplus in the dairy sector resulting in an export of manure. Since dairy farms are spread across the Netherlands, and dairy manure has a favourable composition for direct application on agricultural land, most of the manure exported from the dairy farming system is used on the agricultural land of other farming sectors in the region (J. Roefs, personal communication, April 14, 2021). This way, the decrease of manure due to the different scopes of circularity directly affects the availability of fertilizers for crop production within the Netherlands. Thus, any reduction in herd size of dairy cattle could have negative implications for crop production in the Netherlands.

Agriculture is responsible for 88% of the total NH_3 emissions within the Netherlands for which circa 50% is related to the dairy farming sector (Wemmenhove & Sêbèk, 2021). The results exhibit a decrease in NH_3 emissions from emissions in the shed resulting from the decreasing scope of circularity of 15% in scenario B and 28% in scenario C. The reduction of NH_3 emissions fit the Dutch Nitrogen Policy which aims to decrease the RE content of the total feed intake of dairy cattle to ensure that 50% of the Natura 2000 areas meet the critical deposition value in 2030 (*Structurele Aanpak Stikstofreductie En Natuurversterking*, 2018; van Schouten, 2020). The critical deposition value is the value established for which deposition remains below the risk standards and accordingly does not pose a risk to nature quality (Vink et al., 2021). The changes in total N emissions in the scenarios only account for a reduction of 8% in scenario B and 16% in scenario C. The Nitrogen Policy reduction target requires a generic N emission reduction of 26% by 2030 according to the Dutch government (van Schouten, 2020). With this target, the government deviates from the advised target of 50% by the Advisory Board Nitrogen Problems (Remkes et al., 2020). The results show that considering feed induced N emission reductions, the government reduction target, let alone the advised 50% reduction, is not met by excluding imports from outside the Netherlands altogether. Thus, a larger intervention in the system is required to reduce the N emissions, which has far-stretched implications for the dairy sector.

Other factors which can influence the emissions of cattle stock, such as intensity of (milk) production, the fertiliser application method, the shed system, and the grazing of livestock (J Zijlstra et al., 2019), did not differ under the different scopes of CA in this research. However, since the largest share of emissions are related to manure in shed and storage (49,5%) and fertiliser application (49,3%), these factors represent intervention points into the system. One way to decrease the emissions from shed and storage is by increasing the grazing of dairy cattle. NH_3 is released after conversion of urea when urine comes into contact with manure. During grazing, urine and manure are excreted at different places whereas the NH_3 emissions is much lower than in the stable (C. Alan Rotz et al., 2009). Besides grazing, diverse stable systems are developed to reduce the contact of manure and urine. An overview of the different stable systems to reduce NH_3 emissions can be found in Reijs et al. (2021).

Compared to conventional farming, the average soil surplus in organic farming is 74 kg N per ha lower (Mollenhorst & de Haan, 2021). This difference is related to the use of fertilizers. The results show that in conventional farming the chemical fertilizer application amounts to 115 kg N per ha. On organic dairy farms no chemical fertilizer is used. Furthermore, no derogation is used in organic farming and as a result the animal manure use is set on maximum of 170 kg N per ha (Plomp & Migchels, 2021) compared to an average of 237 kg N per ha in conventional farming (Hoogeveen, 2021). In organic farming the N requirement of crops is met by using leguminous crops to fix N, such as clover and alfalfa (Jelle Zijlstra et al., 2019). A reduction in chemical fertilizer input, and an increase in leguminous crops, could be an effective intervention point to make the dairy farming system more circular. However, the average net yields of organic farms are 0 to 20% lower for feed crops compared to conventional farming (Oenema et al., 2010). Thus, either an increase of the same share of land is required or a decrease in cattle stock akin the reduction in feed produced.

5.2 Research Implications

The results of this study are in line with current research with regards to N emissions of the dairy farming system. By means of Sankey diagrams, the results clearly show the different scopes of circularity and where the potential lies for making the dairy farming system more circular. The discussion has related to potential intervention points to current policy documents and advice on reductions of N emissions, increases of protein self-sufficiency, and CA. The agricultural sector is currently on a crossroad where important decisions concerning the N emissions, climate goals, and biodiversity are expected to largely affect the sector (Vink et al., 2021). For this reason, the policy advice of Remkes et al. (2020) and Vink et al. (2021), suggests that government intervention in the N crisis, should involve climate targets, and the European Habitats Directive in its N policy. Without a holistic approach to the current crisis at hand, the danger is that approaches to by farmers to tackle one issue, might not suffice for another, resulting in stranded assets (Remkes et al., 2020; Vink et al., 2021).

Improving the circularity of the Dutch dairy sector plays an important role due to its large impact on N emissions, biodiversity, and climate. This research quantified and visualised the N flows through the entire Dutch dairy sector and therewith provided insight into which steps can be taken to reach circularity on three different scopes. According to the results, the largest import streams into the system are feed, and chemical fertilizer, and the largest export streams out of the system are N emissions from manure, soil surplus, and milk production. Decreasing these import and output streams would improve the circularity of the dairy farming system for all scopes of circularity.

This research has aimed to contribute to increasing the mineral circularity of the Dutch dairy farming system and therewith aimed to provide a helping hand in determining the scope of circularity for future policy by mapping three scopes of circularity, the influence of these scopes on dairy stock, production and, especially, N emissions, and the potential intervention points into the system.

5.3 Research Limitations

The static model is a systemic approach to quantify and visualise the current N flows in the dairy farming industry. The static model is based on both calculations and literature review. As such, the quality of the model heavily depends on the quality of the data used. Especially the feed types of which singular and compound feed composition differs every quarter depending on the price of feed (R. Goselink, personal communication, May 7, 2021). The effect these differences have on the percentage imports from outside Europe and outside the Netherlands is expected to be little, since most protein crops are produced outside Europe (SOURCE).

The feed intake of dairy cattle in the scenarios is based on the energy and protein requirement of dairy cattle. However, besides these factors VEM, RE, DVE, other components are not considered in this research. The structure of the feed was not considered since this is related to enough roughage in the feed composition and this only increases with the decrease in feed imports. Other factors which are not taken into account, but might influence the dairy stock and production are, for example, the unresistant starch, saturation value, quantity intake of feed, mineral intake, and taste (Verhoeven & Smale, 2014). Also, the feed composition is not adjusted in the three different scenarios, while the composition might not be optimal for dairy cattle. Table 7 displays the N intake and N excretion per milk cow per year in the three different scenarios. Although in scenario B, the N intake and excretion decreases, in scenario C the N intake and excretion increase. This increase can be explained by a relatively high roughage intake per cow. This thesis has not changed the feed composition besides reducing the imports, since adjusting the feed composition requires expert knowledge on how this should be done. As a result, the cattle stock and milk production under the different scopes might portray the most positive scenario.

Table 7. *The N intake, manure excretion and emissions per milk cow per year in scenario A, B, and C.*

	Scenario A	Scenario B	Scenario C
N in feed intake	194,06	192	205,82
N excretion - Manure	128,28	127,22	139,69
N excretion - emissions	14,90	14,28	15,26

Besides, this research assumes a reduction in milk production and cattle stock corresponding to the decrease of imports from outside Europe or the Netherlands. However, as is stipulated in Nationale Eiwitstrategie (2020), the scope of circularity might be accompanied with an increase in feed production. This thesis assumes only an elimination of feed and no substitution of production within the same scope since this is dependent on many uncertainties.

Lastly, the Dutch dairy farming system is portrayed in generic N flows, while there are large differences between farms concerning input, import, output, and export through the system. This thesis is written for the purpose of portraying the N flows in different scopes for the purpose of a reduction in generic

N emissions. The generic approach aims to provide new insights into the current and future situation. Policy can use the insights of this research to aim for a specialised approach instead.

5.4 Further Research

One of the limitations of this research is the simplified approach to feed requirements and intake. Further research into the (optimal) feed intake and composition on the different scopes of circularity would lower these limitations and improve accuracy of the results. For example, the feed intake of dairy cattle might be lower than portrayed in the different scenarios which could result in a larger decrease in cattle stock and production.

In this research, some factors are presumed equal to the year 2018, while they might be subjected to a change. For example, the N application standards, the grazing days, and the milk production per milk cow are assumed equal. Including the past trends in the future scenarios could increase the accuracy of the results.

Policy advise includes advice to look at climate policies, biodiversity policies and N policies simultaneously. Therefore, it would be interesting to repeat this research for methane (CH_4) emissions. By mapping out the methane flows through the dairy farming system, insight can be provided into the intervention points into the system. If the intervention points in the CH_4 and N system align, this could lead to an integral approach to tackle both issues at once. For biodiversity, a more localised approach is needed, since the impact on biodiversity of the emission depends on the location of emissions (Vink et al., 2021). Consequently, it might be interesting to repeat this research on a more localised manner, by dividing the country into different components based on the nature areas as well as the soil types.

The dairy farming sector is directly related to the arable agricultural sector since part of the manure produce by dairy cattle is exported to their land. As such, an extension of this research to the include the arable farming sector might provide more insight into how interventions in the dairy farming sector impacts the arable farming sector.

The decrease in imports of feed for dairy cattle and the decrease in export of dairy products not only affects the Dutch dairy sector, but also affects the importing or exporting country. The impact the Dutch policies can have on second and third countries are not specifically mentioned in one of the policy documents used in this thesis, while the impact these changes could have on the economic, social, and environmental situation of these countries could be substantial. Therefore, research in how different Dutch policy proposals for circular agriculture affect other countries would fill this research gap.

Lastly, the vision of CA of the Ministry of LNV portrays the Netherlands as a frontrunner in CA (Dolman et al., 2019; Ministerie van LNV, 2019a), which implies more countries to follow its example. Therefore, it would be interesting how other (European) countries implementing the same strategy affects the possible scopes for circularity. With the substitution of non-European protein-sources, for example, a production of 17-million-ton protein crops is needed (Dolman et al., 2019). The deficiency to substitute this production, could have enormous consequences for the EU’s agricultural system.

6.Conclusions

N is one of the most important nutrients in agriculture as it is used by plants and animals for metabolic processes, body maintenance, growth, and production (W. de Vries & Schulte-Uebbing, 2019; FAO, 2017; Meeusen et al., 2003). At the same time, however, due to the intensive production system, there is a large N surplus leading to environmental impacts, such as biodiversity loss, and a decrease in water and soil quality (W. de Vries et al., 2021). In the Netherlands, this N surplus has led to the so-called N crisis which impacts several sectors (Remkes et al., 2020). Since the agricultural sector is the largest contributor to N deposition in the Netherlands, a large part of the policy related to N emissions is focused on this sector (Bergevoet et al., 2019). Especially, the dairy farming sector is subject to heated debates about how to reduce the N emissions (Ploegmakers et al., 2020). The reduction in N emissions matches the vision for CA of the Ministry of LNV to reduce losses in the mineral cycles in agriculture (Ministerie van LNV, 2019b, 2019a). This research has quantified for the first time the implications of three different scopes for circularity in the Dutch dairy sector for dairy cattle, production, and N emissions by eliminating feed imports from outside Europe and outside the Netherlands.

The results of this thesis show that the Netherlands imports large quantities of N embedded in feed products, which is partly converted to animal products and partly results in N losses to the environment in dairy cattle excretion. The resulting emissions cause environmental degradation and social and political crisis in the Netherlands (de Wolf et al., 2019; Dolman et al., 2019). The largest emissions in the dairy farming system result from manure excretion and storage, and from fertilizer application. A decrease in the imports of feed for dairy, results in lower emissions from the sector, and, thus, has a positive effect on the environment. The decrease in emissions is mainly related to the reduction in cattle stock and the change in feed composition as a result of the scopes of circularity. Both cattle stock and feed composition contribute to Dutch policies and policies advise of, for example, decreasing N emissions of the livestock sector (van Schouten, 2020), protecting biodiversity and water quality (Erisman & Verhoeven, 2019), and decreasing the protein content of feed (de Haan, 2020; Ministerie van LNV, 2019b). Fertilizer application is not changed under the different scenarios, but could contribute to policy plans, such as, the Realisation Plan of CA (Ministerie van LNV, 2019b) by reducing the input of chemical fertilizers and optimally utilize the fertilizers. Both activities could simultaneously decrease the soil surplus on the arable land. From the results it becomes clear that none of the scopes of circularity directly affects the Dutch consumption of dairy products, as we can comfortably produce sufficient dairy for local demand using feed produced within the Netherlands. However, reducing N imports will affect the social-economic situation of dairy farmers, and the feed exporting and dairy importing countries as our production and exports will reduce by 31%, requiring farmers to reduce herd size, which may likely lead to farmers stepping away from agriculture and large-scale farms further consolidating. Although only eliminating all feed imports is not enough to reach the policy target of the Dutch government of a reduction in N emissions of 26% by 2030 (van Schouten, 2020), the reduction in feed imports could contribute to the Dutch agricultural system reaching its environmental sustainability targets. To do so, it requires careful management to avoid negatively impacting social sustainability factors among producers and stakeholders in trading countries.

The agricultural sector is currently on a crossroad where important decisions concerning the N emissions, climate goals, and biodiversity are expected to largely affect the dairy farming sector (Vink et al., 2021). Improving the circularity in this system plays an important role in this process. This research has contributed to the knowledge on the different scopes of CA and the implications for N flows through the dairy farming system. Therewith, it has provided a systemic analysis of the implications of CA for the dairy stock and production and revealed the potential intervention points into the system for future policy application.

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Appendices

Appendix A: Roughage Production system

This appendix provides the data used in the roughage production system. First, the cultivated crops, and the corresponding area and maximum N utilisation space are given. The maximum N utilisation space is the maximum N that may be legally added the soil of a certain crop type. Second, the N fertilizer input, the amount of N applied to the soil on dairy farms in 2018, is provided.

A.1 Nitrogen Input

Table 8 provides an overview of the cultivated crops on dairy farms in 2018, the area of the cultivated crop, and the maximum N utilisation space. The cultivated crops and corresponding cultivated area are retrieved from StatLine (*Landbouw; Gewassen, Dieren En Grondgebruik Naar Bedrijfstype, Nationaal*, 2021). The maximum N utilisation space for crops is retrieved from the RVO (RVO, 2020).

Table 8. *The cultivated crops on dairy farms in 2018 in hectares (ha) and their maximum N utilisation space (Kg N/ha). The cultivated crops and areas are retrieved from CBS Statline (2021). The maximum N utilisation space is the maximum N which is legally allowed to apply to a specific crop type. The maximum utilisation space for crops is retrieved from RVO (2020).*

Cultivation Type	Area (Ha)	Maximum N Utilisation Space (Kg N/Ha)
Grassland and fodder crops	**827.132,36**	**342***
Grassland	**718.017,85**	**366***
Grassland Temporary	1.707.02,60	310
Grassland Permanent	511.165,97	385
Grassland Natural	36.149,28	0
Fodder crops	**109.114,51**	**183***
Maize silage	106.731,45	160/185***
Fodder beets	1.036,99	165
Lucerne	945,42	40/0
Other green fodder crops	400,65	150
Arable farming	**21.321,69**	**180***
Potatoes	**7.391,41**	**231***
Consumption potatoes	4.687,17	250
Starch potatoes	1.762,84	240
Seed potatoes	941,40	120
Cereals	**6.855,19**	**188***
Wheat	4.059,10	225,6**
Wheat winter	*3.230,14*	*245*
Wheat summer	*828,96*	*150*
Barley	1.562,67	125,5
Winter barley	*372,74*	*140*
Summer barley	*1.189,93*	*80*
Maize grain	445,29	160/185***
Triticale	267,31	160
Rye	254,58	140
Other grains	97,23	188**
Corncob mix	94,75	160/185***
Oats	74,26	100
Grass seeds	40,67	165
Vegetables	**1.632,87**	**118***
Onions	826,90	120
Carrot	223,76	110
Winter carrot	122,17	110
Peas	115,71	30
Green beans	107,66	120
Salsify	69,59	170
Spinach	43,19	185

Celeriac	24,90	200
Rutabaga	22,47	170
Sweet corn	16,78	200
Beetroot	15,32	185
Broad beans	8,58	75
Chicory root	4,56	100
Kale	1,28	170
Trade crops	**384,23**	**107***
Chicory	111,19	70
Hemp	91,59	107**
Cabbage and rapeseed	84,73	158*
Cabbage and rapeseed winter	*37,58*	*205*
Cabbage and rapeseed summer	*47,15*	*120*
Soybeans	56,91	107**
Sunflowers	19,10	107**
Flax	8,21	70
Other trade crops	2,50	107**
Legumes	**218,84**	**144***
Sugar beets	3.767,03	150
Braak	414,30	144**
Other arable crops	255,15	144**
Field beans	197,56	50
Fodder peas	18,91	30
Broad beans	2,37	75
Other arable crops	**255,15**	**180***
Horticulture	**903,70**	**165***
Vegetables	**384,18**	**178***
Asparagus	98,24	85
Head cabbage	44,27	285
Salad	38,35	180/105***
Leeks	31,91	245
Cucumber-like	33,95	190
Carrot	26,42	50
Other	21,60	178**
Broccoli	21,25	270
Brussels sprouts	17,75	290
Cauliflower	16,12	230
Growing material	13,25	178*
Rhubarb	7,68	250
Parsnip	5,37	178**
Chinese cabbage	5,35	180
Strawberries	1,26	170
Fennel	1,09	180
Endive	0,18	180/90
French beans	0,12	120
Kohlrabi	0,02	180
Flower bulbs and tubers	**250,96**	**190***
Tulips	180,96	200
Lilies	34,28	155
Gladiolus	24,32	190
Dahlia	6,33	110
Daffodils	2,84	145
Other	2,23	190**
Fruit open ground	**135,30**	**174***
Pome and stone fruits	133,41	174**
Apples	*17,45*	*175*
Pears	*28,38*	*175*
Plums	*0,74*	*175*
Sweet cherry	*2,79*	*175*
Other pome and stone fruits	*84,05*	*174***

Small fruit	0,74	138*
Blueberries	*0,04*	*100*
Redcurrants, raspberries, blackberries	*0,13*	*150*
Other	*0,57*	*138***
Wine grapes	1,15	100
Tree nursery and perennials	**119,31**	**97***
Ornamental conifers	36,20	80
Fruit trees	23,47	110
Forest and hedge planting stock	20,50	95
Avenue and park tress	18,84	90
Perennials	7,74	175
Buxus	6,60	95
Rose bushes	3,52	70
Ornamental shrubs and climbing plants	2,12	75
Climbing plants	0,32	80
Flower nursery crops	**13,74**	**98***
Other	5,89	98**
Other cut flowers	5,23	98**
Dahlia	1,13	110
Flower seeds	0,9	98**
Peony	0,5	70

*This data is calculated from the average maximum utilisation space of N by multiplying the hectares with the maximum amount of N per hectare and dividing it by the total area.
**This data was incomplete and therefore assumed equal to the average.
*** This applicable maximum utilisation space depends on whether a dairy farm has derogation or not.

Table 9 provides an overview of the N fertilizer application on dairy farms in 2018. The fertilizer input is based on the legal maximum N utilisation space retrieved from the RVO (RVO, 2020), and the average N application on dairy farms in 2018 from Agrimatie (*Nutrienten*, 2021). The manure application is based on the legal maximum manure N utilisation space retrieved StatLine (*Dierlijke Mest; Productie En Mineralenuitscheiding, Diercategorie, Regio*, 2021). The chemical fertilizer application is calculated with the method described in section 3.1.2, and the other organic fertilizer application is retrieved from Agrimatie (*Nutrienten*, 2021). The average N fixation, mineralisation, and deposition on dairy farms in 2018 are retrieved from Agrimatie (*Nutrienten*, 2021) and account for 7,42 kg per ha, 20,77 kg per ha, and 21,14 kg per ha.

Table 9. *The fertilizer input on dairy farms in 2018 in kg per ha. The fertilizer input is divided in the manure of which 60% is the efficient part, chemical fertilizer, and organic fertilizer.*

Input	**Fertilizer input (Kg N/ha)**	***Of which Manure (Kg N/ha)***	***Of which chemical fertilizer (Kg N/ha)***	***Of which other organic fertilizer (Kg N/ha)***
Grassland and fodder crops	**260**	***243***	***118***	***1,5***
Grassland, temporary	287	*250*	*136*	*1*
Grassland, permanent	287	*250*	*136*	*1*
Grassland, natural	0	*0*	*0*	*1*
Maize silage	185	*250*	*34*	*1*
Fodder beets	165	*167*	*64*	*1*
Lucerne	0	*0*	*0*	*0*
Other fodder crops	150	*167*	*49*	*1*
Arable farming	**180**	***167***	***58***	***21***
Horticulture	**165**	***167***	***64***	***1***

A.2 Nitrogen Output

Table 10 provides an overview of the N yield and soil surplus on dairy farms in 2018. The yield is based on the total N production and the cultivated area from StatLine (CBS StatLine, 2021; *Mineralenbalans Landbouw*, 2020). The soil surplus is calculated as described in section 3.1.2. The average N application emissions are retrieved from Agrimatie (*Nutrienten*, 2021) and account for 27,53 kg per on dairy farms in 2018.

***Table 10**. The average yield and soil surplus in kg N per hectare on dairy farms in 2018.*

Output	**Yield (Kg N/ha)**	**Soil surplus (Kg N/ha)**
Grassland and fodder crops		
Grassland	236	153
Maize silage	170	136
Fodder beets	129	125
Lucerne	380	-357
Other fodder crops	130	108
Arable farming	**132**	**136**
Horticulture	**161**	**93**

Appendix B: Dairy Production System

This appendix provides the calculations of the N flows through dairy cattle used in the methodology of this thesis. First, the general equation for N flows through dairy cattle is given, which consists of the input of N through feed intake, and the output of N through N fixation in growth, gestation and milk and the excretion of N (Equation 1). Second, the calculations for N intake are given in section B.1. The N intake is calculated by multiplying a feed product with its N content and adding the N intake of every product. Third, the calculations for N fixation are given in section B.2. Depending on the dairy cattle category, N is fixed in growth, gestation, and milk production. Fourth, the calculations for N excretion are given in section B.3. The total gross N excretion can be calculated by subtracting N fixation from the total N feed intake. The part of the N excretion, which is lost through N emissions, excreted in the pasture, or excreted in the shed is determined with further calculations dependent on the grazing days and hours and the feed types and digestion coefficient. Lastly, the calculations for the number of dairy cattle stocks are given in section B.4. The N intake through feed, the fixation of N in growth, gestation and milk, and the N excretion of cattle all depend on the number of dairy cattle. The quantity cattle are determined by means of the total availability of energy (VEM) and protein (DVE) and their requirements per cow.

B.1 Nitrogen intake

In the following equations, the N intake by dairy cattle is calculated. N intake, is the N which is fed to dairy cattle, including the N intake through feed commodities and the feeding losses. The feeding losses are included since these losses end up as part of the N in manure. To calculate the N intake in dairy cattle, the quantity DS intake for each feed commodity is multiplied with its N content. The N intake of each feed commodity is added to obtain the total N intake through feed for a dairy cattle category (DCC). The calculations are retrieved from Handreiking Bedrijfsspecifieke Excretie Melkvee (2019). The quantity feed intake per dairy cattle category is retrieved from van Bruggen & Gosseling (2019), the feed commodities of which compound feed consists is retrieved from personal communication (F. Gort, personal communication, March 3, 2021), the feed commodities of which singular feed consist are retrieved from de Kleijne et al. (2018) and Remmelink et al. (2020), the feed commodities of which moisture rich feed is retrieved from Afzet Vochtrijke Diervoeders Neemt Toe (2018), and the N content of the feed commodities is retrieved from Blok & Spek (2018) for the year 2018. Table 12 contains the explanation of the variables used in the equations for N intake of dairy cattle.

With the following equations, the N intake of dairy cattle can be calculated:

$$Nintake = Nfixation + Nexcretion \qquad \text{(Kg N/year) (Eq. 1)}$$

$$Nintake = Nintake_{MC} + Nintake_{YS<1} + Nintake_{YS>1} \qquad \text{(Kg N/year) (Eq. 2)}$$

$$Nintake_{DCC} = Qfeed_{n1_{DCC}} \cdot Ncont_{n1} + Qfeed_{n2_{DCC}} \cdot Ncont_{n2} + Qfeed_{nx_{DCC}} \cdot Ncont_{nx} \qquad \text{(Kg N/year) (Eq. 3)}$$

Table 11. *The explanation of the variable used in the equations for feed intake of dairy cattle.*

Variables	Explanation
N intake	
Nintake	The amount of N fed to all dairy cattle, including average feeding losses of 2% compound feed, 3% moisture rich feed, 2% milk, and 5% conserved roughage (Kg N/year)

$Nintake_{DCC}$	The amount of N fed to a specific dairy cattle category, including average feeding losses of 2% compound feed, 3% moisture rich feed, 2% milk, and 5% conserved roughage (Kg N/year)
Nfixation	The total N fixed in dairy cattle (Kg N/year)
Nexcretion	The total amount of N in the excretion of dairy cattle including faeces, urine and feeding losses (Kg N/year)
$Qfeed_{nxDCC}$	The total amount of feed of commodity nx provided to a specific DCC (Kg DS). Depending on the scenario Qfeed is equal to the quantity feed produced for dairy cattle in the Netherlands, Europe, excluding the Netherlands, and/or the world, excluding Europe.
$Ncont_{nx}$	The N content of feed commodity nx (Kg N/Kg DS)

B.2 Nitrogen Fixation

In the following equations, the N fixation in dairy cattle is calculated. N fixation is the N fixed in growth, gestation, or milk. To calculate the N fixation in growth, the difference in N at the beginning and the end of a year is determined. The N fixation in gestation is calculated by multiplying the N in a new-born calf with the number of calves born per DCC. The N fixation in milk is calculated by multiplying the quantity milk produced per year with the N content of milk. The calculations differ per DCC, where MC stands for milk cows, YS<1 stands for young stock younger than 1 year, and YS>1 stand for young stock older than 1 year. The calculations are retrieved from Handreiking Bedrijfsspecifieke Excretie Melkvee (2019). Table 13 contains the explanation of the variables and constants used in the equations. The constants are retrieved from CBS StatLine (2021), Handreiking Bedrijfsspecifieke Excretie Melkvee (2019), and van Bruggen & Gosseling (2019).

$$Nfixation = Nfixation_{YS<1} + Nfixation_{YS>1} + Nfixation_{MC} \quad \text{(Kg N/year) (Eq. 4)}$$

With the following equations, the N fixation for young stock younger than 1 year can be calculated:

$$Nfixation_{YS<1} = N_{growth1} \quad \textit{(Kg N/year) (Eq. 5)}$$

Where $$N_{growth1} = \left(N_{calf} - N_{birth1}\right) \cdot Q_{YS<1} \cdot N_{corr} \quad \textit{(Kg N/year) (Eq. 28)}$$

Where $$N_{calf} = \frac{W_{calf} \cdot Ncont_{calf}}{1000} \quad \textit{(Kg N/year) (Eq. 29)}$$

And $$Nbirth1 = \frac{W_{birth} * \cdot Ncont_{birth}}{1000} \quad \textit{(Kg N/year) (Eq. 30)}$$

And $$N_{corr} = (\left(N_{calf} - N_{birth1}\right) \cdot \frac{0,376}{0,407} + \frac{N_{fixation1mnth}}{2} \cdot 24 \cdot \frac{0,031}{0,407}) / \left(N_{calf} - N_{birth1}\right) \quad \textit{(Kg N/year) (Eq. 31)}$$

With the following equations, the N fixation in young stock older than 1 can be calculated:

$$Nfixation_{YS>1} = N_{growth2} + N_{gestation1} \quad \textit{(Kg N/year) (Eq. 6)}$$

Where $$N_{growth2} = \left(N_{heifer1} - N_{calf}\right) \cdot \frac{12}{14} \cdot Q_{YS>1} \quad \textit{(Kg N/year) (Eq. 32)}$$

Where $$N_{heifer1} = \frac{W_{heifer} \cdot Ncont_{heifer}}{1000} \quad \textit{(Kg N/year) (Eq. 33)}$$

And $$N_{gestation1} = N_{birth2} = \frac{W_{birth} * C_{heifer} \cdot Ncont_{calf}}{1000} \cdot Q_{YS>1} \quad \textit{(Kg N/year) (Eq. 34)}$$

With the following equations, the N fixation in milk cows can be calculated:

$$Nfixation_{MC} = N_{growth3} + N_{gestation2} + N_{milk} \quad \textit{(Kg N/year) (Eq. 7)}$$

$$Where\ N_{growth3} = (N_{Cow} - N_{heifer}) \cdot Q_{MC}$$ (Kg N/year) (Eq. 35)

$$Where\ N_{cow} = \frac{W_{cow} \cdot Ncont_{cow}}{1000}$$ (Kg N/year) (Eq. 36)

$$And\ N_{heifer2} = \frac{W_{heifer} \cdot S_{cow} \cdot Ncont_{heifer}}{1000}$$ (Kg N/year) (Eq. 37)

$$And\ N_{gestation2} = \left(\frac{W_{birth} \cdot C_{cow} \cdot Ncont_{birth}}{1000}\right) \cdot Q_{MC}$$ (Kg N/year) (Eq. 38)

$$And\ N_{milk} = \left(\frac{Q_{milk} \cdot Ncont_{milk}}{1000}\right) \cdot Q_{MC}$$ (Kg N/year) (Eq. 39)

$$Where\ Ncont_{milk} = \%protein \cdot \frac{10}{6{,}38}$$ (Kg N/year) (Eq. 40)

Table 12. *The constants and variables used in the calculations of the fixation of N in young stock and milk cows. The constants for the year 2018 are retrieved from CBS StatLine (2021), RVO (2019) and van Bruggen & Gosseling (2019).*

Abbreviation	**Explanation**	**Number**
Variables		
N fixation		
Nfixation	The total N fixed in dairy cattle (Kg N/year)	
Nfixation DCC	The total N fixed in a specific dairy cattle category (DCC) (Kg N/year)	
Ngrowth1	The N fixed in growth of young stock younger than 1 year (Kg N/year)	
Ngrowth2	The N fixed in growth of young stock older than 1 year (Kg N/year)	
Ngrowth3	The N fixed in growth of milk cows (Kg N/year)	
Ngestation1	The N fixed in young stock older than 1 year for pregnancy (Kg N/year)	
Ngestation2	The N fixed in milk cows for pregnancy (Kg N/year)	
Ncalf	The N in young stock of 12 months old (calf) (Kg N/year)	
Nbirth1	The N in young stock at birth (Kg N/year)	
Nbirth2	The N in young stock at birth multiplied with the number of calves born per young stock older than 1 year (*Cheifer*) (Kg N/year)	
Nheifer1	The N in (pregnant) young stock of 15 months old (heifer) (Kg N/year)	
Nheifer2	The N in (pregnant) young stock of 15 months old (heifer) multiplied with the number of young stocks born per cow (*Ccow*) (Kg N/year)	
Ncow	The N in milk cows of (at least) 24 months (Kg N/year)	
Nmilk	The N content of milk multiplied with the quantity milk produced by dairy cattle per year (Kg N/year)	
Ncorr	The correction factor for the average number of months presents in dairy farms	
Constants		
Quantity		
Qys<1	The number of young stock younger than 1 year in 2018 (cows)	429.000
Qys>1	The number of young stock older than 1 year in 2018 (cows)	521.000
Qmc	The number of milk cows in 2018 (cows)	1.591.000
Qmilk	The quantity milk produced per milk cow per year in 2018 (Kg milk/cow/year)	8.848
Weight		
Wbirth	Weight of a cow at birth (Kg)	44
Wcalf	Weight of young stock at 12 months old (calf) (Kg)	320
Wheifer	Weight of young stock at 15 months old (heifer) (Kg)	540
Wcow	Weight of a cow at 24 months and older (Kg)	650
N content		
Ncontbirth	N content of young stock at birth (Kg N/Kg)	29,44
Ncontcalf	N content of young stock at 12 months old (calf) (Kg N/Kg)	24,1
Ncontheifer	N content of young stock at 15 months old (heifer) (Kg N/kg)	23,1
Ncontcow	N content of a (milk) cow at 24 months and older (Kg N/kg)	22,5
Ncontmilk	N content of milk in 2018 (Kg N/Kg)	5,58
Milk cow		
%protein	Protein content of milk produced by milk cows in 2018 (%)	3,56
Ccow	Number of calves born per milk cow per year in 2018	0,70
Scow	Substitution fraction per milk cow in 2018	0,28
Young stock		

Cheifer	Number of young stock born from young stock older than 1 per year in 2018	0,79
Nfixation1mnth	The N fixation in one month of young stock younger than 1 year (Kg N/cow/month)	0,36

B.3 Nitrogen Excretion

In the following equations, the N excretion in dairy cattle is calculated. The gross N excretion is the N excreted by dairy cattle in the form of gaseous losses and manure. To calculate the gross N excretion, the N fixed in growth, gestation and milk is subtracted from the total N intake through feed. The net N excretion is the gross N excretion minus the gaseous losses of N. The Gaseous losses of N consist of NH_3 emissions in the shed, other N emissions in the shed, and N emissions in external storage of manure. The N emissions in external storage are calculated by subtracting the NH_3 emissions and other N losses from the shed from the total gaseous losses. The other N emissions in the shed are calculated by multiplying the N in the manure with an emission factor of 0,024. The NH_3 emissions are strongly dependent on the total ammoniacal N (TAN), which is the part of N in manure which is easily convertible to NH_3. The TAN is dependent on the grazing period and the digestibility of the feed. Table 14 contains the explanation of the variables and constants used in the equations. The equations are retrieved from Handreiking Bedrijfsspecifieke Excretie Melkvee (2019), and the constants are retrieved from CBS StatLine (2021) and van Bruggen & Gosseling (2019).

The N excretion of dairy cattle is calculated with the following equations:

$Nexcretion = Nexcretion_{MC} + Nexcretion_{YS<1} + Nexcretion_{YS>1}$ (Kg N/year) (Eq. 8)

With the following equation, the gross N excretion for the dairy cattle categories can be calculated:

$Nexcretion_{DCC} = Nintake_{DCC} - Nfixation_{DCC}$ (Kg N/year) (Eq. 9)

With the following equation, the net N excretion can be calculated:

$Nexcretion_{net_{\mathrm{DCC}}} = Nexcretion_{\mathrm{DCC}} - Ngass_{\mathrm{DCC}}$ (Kg N/year) (Eq. 10)

With the following equation the total gaseous N losses of dairy cattle can be calculated:

$Ngass = Ngass_{MC} + Ngass_{YS<1} + Ngass_{YS>1}$ *(Kg N/year) (Eq. 11)*

$Ngass_{DCC} = Nemission_{NH3_{DCC}} + Nemission_{stable_{DCC}} + Nemission_{storage_{DCC}}$ *(Kg N/year) (Eq. 12)*

With the following equations the NH_3 emissions in the shed are calculated:

$Nemission_{NH3_{DCC}} = Fraction_{shedseason_{DCC}} \cdot TAN_{shed_{DCC}} \cdot 0{,}143 + Fraction_{grazingseason_{DCC}} \cdot TAN_{shed_{DCC}} \cdot 0{,}165$
(Kg N/year) (Eq. 41)

Where $Fraction_{shedseason_{DCC}} = (365 - Q_{grazingdays_{DCC}})/365$ *(Eq. 42)*

And $Fraction_{grazingseason_{DCC}} = Q_{grazingdays_{DCC}}/365$ *(Eq. 43)*

And $TAN_{shed_{DCC}} = TANexcr._{shed_{DCC}} + ((Nexcr._{shed_{DCC}} - TANexcr._{shed_{DCC}}) \cdot 10\%)$
(Kg N/year) (Eq. 44)

Where $TANexc._{shed_{DCC}} = TANexcr._{DCC} \cdot Fraction_{shedhours_{DCC}}$ *(Kg N/year) (Eq. 45)*

$$Where\ \ TANexcr._{DCC} = Nexcr._{urine\,DCC} = (N_{intake\,DCC} \cdot VC\_RE_{DCC} \cdot 0{,}91) - N_{fixation\,DCC}$$ *(Kg N/year) (Eq. 46)*

$$Where \quad VC\_RE_{DCC} = {VRE_{intake\,DCC}}/{RE_{intake\,DCC}}$$ *(g VRE/g RE) (Eq. 47)*

$$Where\ RE_{intake} = N_{intake} \cdot 6{,}25$$ *(Kg RE/year) (Eq. 48)*

$$And\ \ VRE_{intake\,DCC} = VREcont_{n1} \cdot Qfeed_{n1\,DCC} + VREcont_{n2} \cdot Qfeed_{n2\,DCC} + VREcont_{nx} \cdot Qfeed_{nx\,DCC}$$ *(Kg VRE/year) (Eq. 49)*

$$And\ Fraction_{shedhours\,DCC} = 1 - (Q_{grazingdays\,DCC} \cdot Q_{grazinghours\,DCC} \cdot \tfrac{315}{365})/(24 \cdot 365)$$ *(Eq.50)*

$$And\ Nexcr._{shed\,DCC} = Nexcr._{DCC} \cdot Fraction_{shedhours\,DCC}$$ *(Kg N/year) (Eq. 51)*

$$Where\ \ Nexcr._{DCC} = Nexcr._{urine\,DCC} + Nexcr._{feaces\,DCC}$$ *(Kg N/year) (Eq. 52)*

$$Where \quad Nexcr._{urine\,DCC} = (N_{intake\,DCC} \cdot VC\_RE \cdot 0{,}91) - N_{fixation}$$ *(Kg N/year) (Eq. 53)*

$$And \quad Nexcr._{feaces} = N_{intake} \cdot (1 - VC\_RE \cdot 0{,}91)$$ *(Kg N/year) (Eq. 54)*

With the following equations the N emissions in the shed other than NH_3 are calculated:

$$Nemission_{stable\,DCC} = Nexcr._{shed\,DCC} \cdot 0{,}024$$ (Kg N/year) (Eq. 55)

With the following equations the N emissions in storage are calculated:

$$Nemission_{storage} = (Nstable_{manure} - Nemission_{NH3} - Nemission_{stable}) \cdot 20\% \cdot 1\%$$ *(Kg N/year) (Eq. 56)*

Table 13. *The variables and constants used in the calculations of N excretion of young stock and milk cows. The constants are retrieved for the year 2018 from CBS StatLine (2021) and van Bruggen & Gosseling (2019).*

Abbreviation	**Explanation**	**Number**
Variables		
Feed intake		
Nintake	The amount of N fed to all dairy cattle, including average feeding losses of 2% compound feed, 3% moisture rich feed, 2% milk, and 5% conserved roughage (Kg N/year)	
Nintake DCC	The amount of N fed to a specific dairy cattle category, including average feeding losses of 2% compound feed, 3% moisture rich feed, 2% milk, and 5% conserved roughage (Kg N/year)	
VC_RE	The digestion coefficient per ration (g VRE/g RE)	
VRE intake	The total digestibility of the RE (g VRE)	
RE intake	The total protein intake of a specific dairy cattle category (g RE)	
N intake	The total N intake through of dairy cattle (Kg N/year)	
N fixation		
Nfixation DCC	The amount of N which is fixed in animal growth, gestation and/or milk production in a specific dairy cattle category (Kg N/year)	
N excretion		
Nexcretion	The total amount of N in the excretion of dairy cattle including faeces, urine and feeding losses (Kg N/year)	
Nexcretion DCC	The amount of N in the excretion of dairy cattle including faeces, urine and feeding losses per dairy cattle category (Kg N/year)	
$Nexcretion_{net}$ DCC	The net N excretion, or N in manure, after subtraction of losses of a specific dairy cattle category (kg N/year)	
$Nexcr._{urine}$	The total amount of N excreted in urine (Kg N/year)	

$Nexcr._{faeces}$	The total amount of N excreted in faeces (Kg N/year)	
$Nexcr._{shed}$	The amount of N which is excreted in the shed (Kg N/year)	
Nexcr.	The total N excretion of a dairy cattle (Kg N/year)	
TAN		
TAN_{shed} DCC	The part of the TAN excreted which is emitted (Kg N/year)	
$TANexcr._{shed}$	The amount of TAN which is excreted in the shed (Kg N/year)	
TANexcr. DCC	The total TAN excretion of a dairy cattle category (Kg N/year)	
N emissions		
Ngass	The total gaseous losses from manure in the shed and external storage (Kg N/year)	
Ngass DCC	The gaseous losses from manure in the shed and external storage per dairy cattle category (Kg N/year)	
$Nemissions_{NH3}$ DCC	The gaseous NH_3 emissions from manure per dairy cattle category (Kg N/year)	
$Nemissions_{stable}$ DCC	The gaseous N emissions from the shed per dairy cattle category (Kg N/year)	
$Nemissions_{storage}$ DCC	The gaseous N emissions from storage per dairy cattle category (Kg N/year)	
Fractions		
$Fraction_{stableseason}$ DCC	The share of manure which is excreted in the housing season by a specific dairy cattle category	
$Fraction_{grazingseason}$ DCC	The share of manure which is excreted in the grazing season by a specific dairy cattle category	
$Fraction_{shedhours}$ DCC	The share of hours that a dairy cattle category spends in the shed on an annual basis	
Constants		
Grazing		
$Q_{grazingdays\ YS<1}$	The number of days which young stock younger than 1 year spends grazing in 2018 (days/year)	43,25
$Q_{grazingdays\ YS>1}$	The number of days which young stock older than 1 year spends grazing in 2018 (days/year)	89,9
$Q_{grazingdays\ MC}$	The number of days which milk cows spend grazing in 2018 (days/year)	159
$Q_{grazinghours\ YS<1}$	The number of hours which young stock younger than 1 year spends grazing on a grazing day in 2018 (hours/day)	24
$Q_{grazinghours\ YS>1}$	The number of hours which young stock older than 1 year spends grazing on a grazing day in 2018 (hours/day)	24
$Q_{grazinghours\ MC}$	The number of hours which milk cows spend grazing on a grazing day in 2018 (hours/day)	6
Feed commodity		
VREcont nx	The digestibility of the RE of a feed commodity nx (g VRE/Kg DS)	
$Qfeed_{nxDCC}$	The total amount of feed of commodity nx provided to a specific DCC (Kg DS). Depending on the scenario Qfeed is equal to the quantity feed produced for dairy cattle in the Netherlands, Europe, excluding the Netherlands, and/or the world, excluding Europe.	

B.4 Livestock Quantity

In the following equations, the quantity livestock is calculated. The quantity livestock is calculated by dividing the VEM and DVE requirement per cow by the total VEM and DVE availability in feed per dairy cattle category. The VEM and DVE availability are calculated by multiplying the quantity feed of a commodity with its VEM or DVE content and adding the results for each feed commodity. The VEM requirement is calculated by adding the VEM needed for subsistence, grazing, gestation, lactation, and milk production depending on the dairy cattle category. The VEM needed for subsistence and gestation are given in Table 15. The VEM required for grazing is calculated by means of the number of grazing days per year. The VEM needed for lactation and milk production is calculated by means of the protein and fat content of milk (FPCM). The DVE requirement is calculated by adding the DVE required for subsistence, growth, gestation, youth and/or milk production depending on the dairy cattle category.

The DVE needed for growth, gestation, and youth are provided in **Table 15**. The DVE requirement for subsistence is dependent on the weight of dairy cattle, and the DVE requirement for milk production is dependent on the protein content and quantity milk produced per milk cow per year. The equations for DVE and VEM availability and requirements are retrieved from Duinkerken & Spek (2016). The constants are retrieved from CBS StatLine, (2021), van Bruggen (2011) and Duinkerken & Spek (2016).

The quantity of a dairy cattle category (DCC) is calculated with the following equations:

$QDCC = MIN(QDCC_{VEM}, QDCC_{DVE})$ *(cows) (Eq. 13)*

$QDCC_{VEM} = VEMrequirement_{DCC}/VEMavailbility_{DCC}$ *(cows) (Eq. 14)*

$QDCC_{DVE} = DVErequirement_{DCC}/DVEavailbility_{DCC}$ *(cows) (Eq. 15)*

The total VEM and DVE availability per dairy cattle category are calculated with the following equations:

$VEMavailbility_{DCC} = Qfeed_{n1_{DCC}} \cdot VEMcont_{n1} + Qfeed_{n2_{DCC}} \cdot VEMcont_{n2} + Qfeed_{nx_{DCC}} \cdot VEMcont_{nx}$
(VEM/year) (Eq. 16)

$DVEavailbility_{DCC} = Qfeed_{n1_{DCC}} \cdot DVEcont_{n1} + Qfeed_{n2_{DCC}} \cdot DVEcont_{n2} + Qfeed_{nx_{DCC}} \cdot DVEcont_{nx}$
(Kg DVE/year) (Eq. 17)

The total VEM and DVE requirements per cow are calculated with the following equations for young stock younger than 1 year:

$VEMrequirement_{YS<1} = (VEMsubsist_{YS<1} + VEMgrazing_{YS<1}) \cdot 1{,}02$ *(VEM/cow/year) (Eq. 18)*

Where $VEMgrazing_{YS<1} = 346 \cdot \ Q_{grazingdaysYS<1}$ *(VEM/cow/year) (Eq. 57)*

For young stock older than 1 year:

$VEMrequirement_{YS<1} = (VEMsubsist_{YS>1} + VEMgrazing_{YS>1} + VEMgestation_{YS>1}) \cdot 1{,}02$
(VEM/cow/year) (Eq. 19)

$VEMgrazing_{YS>1} = 784 \cdot Q_{grazingdaysYS>1}$

For milk cows:

$VEMrequirement_{MC} = (VEMsubsist_{MC} + VEMgrazing_{MC} + VEMgestation_{MC} + VEMlactation + VEMmilk) \cdot 1{,}02$
(VEM/cow/year) (Eq. 20)

Where $VEMsubsist_{MC} = 42{,}4 \cdot {W_{cow}}^{0{,}75} \cdot (-15 \cdot 0{,}00165)) \cdot 50$ *(VEM/cow/year) (Eq. 58)*

And $VEMgrazing_{MC} = 201000 + Q_{grazingdaysMC} \cdot 419) \cdot 315/365$ *(VEM/cow/year) (Eq. 59)*

And $VEMlactation = 42{,}2 \cdot {W_{cow}}^{0{,}75} \cdot (1 + (FPCM - 15) \cdot 0{,}00165)) \cdot 315$ *(VEM/cow/year) (Eq. 60)*

And $VEMmilk = 442 \cdot FPCM \cdot (1 + (FPCM - 15) \cdot 0{,}00165)) \cdot 315$ *(VEM/cow/year) (Eq. 61)*

Where $FPCM \ = \ Qmilk \cdot (0{,}337 + 0{,}116 \cdot \%fat + 0{,}06 \cdot \%protein))/315$ *(VEM/cow/year) (Eq. 62)*

With the following equations, the DVE requirement per cow can be calculated for young stock younger than 1 year:

$DVErequirement_{YS<1} = (DVEsubsist_{YS<1} + DVEgrowth_{YS<1})$ *(Kg DVE/cow/year) (Eq. 21)*

Where $DVEsubsist_{YS>1} = 54 + (0.1 * W_{calf})$ *(Kg DVE/cow/year) (Eq. 63)*

With the following equations, the DVE requirement per cow can be calculated for young stock older than 1 year:

$DVErequirement_{YS>1} = (DVEsubsist_{YS>1} + DVEgrowth_{YS>1} + DVEgestation_{YS>1})$
(Kg DVE/cow/year) (Eq. 22)

Where $DVEsubsist_{YS>1} = 54 + (0.1 * W_{heifer})$ *(Kg DVE/cow/year) (Eq. 64)*

With the following equations, the DVE requirement per cow can be calculated for milk cows:

$DVErequirement_{MC} = (DVEsubsist_{MC} + DVEyouth_{MC} + DVEgestation_{MC} + DVEmilk_{MC})$
(Kg DVE/cow/year) (Eq. 23)

Where $DVEsubsist_{MC} = 54 + (0.1 * W_{mc})$ *(Kg DVE/cow/year) (Eq. 65)*

And $DVEmilk_{MC} = 1{,}396 * E + 0{,}000195 * (E^2)) * 10$ *(Kg DVE/cow/year) (Eq. 66)*

Where $E = \ Qmilk * \%Protein$ *(Kg DVE/cow/year) (Eq. 67)*

Table 14. *The variables and constants used in the calculations of livestock quantities. The numbers are retrieved from* CBS StatLine, (2021) and van Bruggen (2011)*.*

Abbreviation	**Explanation**	**Constant**
Variables		
Quantity		
QDCC	The quantity of the specific dairy cattle category which can be provided with enough energy and protein from the available feed for intake (cows)	
$QDCC_{VEM}$	The quantity of the specific dairy cattle category which can be provided with enough energy from the available feed for intake (cows)	
$QDCC_{DVE}$	The quantity of the specific dairy cattle category which can be provided with enough protein from the available feed for intake (cows)	
$Qfeed_{nxDCC}$	The total amount of feed of commodity nx provided to a specific DCC (Kg DS). Depending on the scenario Qfeed is equal to the quantity feed produced for dairy cattle in the Netherlands, Europe, excluding the Netherlands, and/or the world, excluding Europe.	
VEM		
$VEMavailability_{DCC}$	The energy available in the total quantity feed available for a dairy cattle category (VEM/year)	
$VEMrequirement_{DCC}$	The energy intake required for subsistence, grazing, gestation and/or milk production for a specific dairy cattle category in 2018 (VEM/cow/year)	
$DVEavailability_{DCC}$	The protein available in the total quantity feed available for a dairy cattle category (Kg DVE/year)	
$DVErequirement_{DCC}$	The protein intake required for subsistence, growth, gestation, and milk production for a specific daiyr cattle category in 2018 (Kg DVE/cow/year).	
VEM_{contnx}	The N content of feed commodity nx provided to dairy cattle (VEM/Kg DS)	
$VEMgrazing_{YS<1}$	The VEM required for the grazing, or movement outside the shed, of young stock younger than 1 year (VEM/cow/year)	

$VEMgrazing_{YS>1}$	The VEM required for the grazing, or movement outside the shed, of young stock older than 1 year (VEM/cow/year)	
$VEMgrazing_{MC}$	The VEM required for the grazing, or movement outside the shed, of milk cows (VEM/cow/year)	
VEMlactation	The VEM required for lactation in milk cows (VEM/cow/year)	
VEMmilk	The VEM required for the production of milk (VEM/cow/year)	
FPCM	Fat and protein corrected milk (FPCM) is the average milk production of milk cows adjusted for its protein and fat content.	
DVE		
DVE_{contnx}	The N content of feed commodity nx provided to dairy cattle (Kg DVE/Kg DS)	
$DVEsubsist_{YS<1}$	The DVE requirement for growth and maintenance for young stock younger than 1 year (Kg DVE/cow/year)	
$DVEsubsist_{YS>1}$	The DVE requirement for growth and maintenance for young stock older than 1 year (Kg DVE/cow/year)	
DVEmilk	The protein required for milk production in dairy cattle (Kg DVE/year)	
Constants		
VEM		
$VEMsubsist_{YS<1}$	The VEM requirement for growth and maintenance for young stock younger than 1 year (VEM/cow/year)	1.323.000
$VEMsubsist_{YS>1}$	The VEM requirement for growth and maintenance for young stock older than 1 year (VEM/cow/year)	2.259.000
$VEMgestation_{YS>1}$	The VEM requirement for gestation of young stock older than 1 year (VEM/cow/year)	2.81.900
$VEMgestation_{MC}$	The VEM requirement for gestation of milk cows (VEM/cow/year)	194.000
VEMyouth	The VEM requirement for taking care of youth by milk cows (VEM/cow/year)	101.000
DVE		
$DVEgrowth_{YS<1}$	The DVE requirement for growth per young stock younger than 1 year (Kg DVE/cow/year)	93.683
$DVEgrowth_{YS>1}$	The DVE requirement for growth per young stock older than 1 year (Kg DVE/cow/year)	146.608
$DVEgestation_{YS>1}$	The DVE requirement for gestation for young stock older than 1 year (g DVE/cow/year)	9.454
$DVEgestation_{MC}$	The DVE requirement for gestation of milk cows (g DVE/cow/year)	4.855
$DVEyouth_{MC}$	The DVE requirement for taking care of youth by milk cows (g DVE/cow/year)	19.010
Other		
Qmilk	The quantity milk produced per milk cow per year in 2018 (Kg milk/cow/year)	8.848
$Q_{grazingdays\ YS<1}$	The number of days which young stock younger than 1 year spends grazing in 2018 (days/year)	43,25
$Q_{grazingdays\ YS>1}$	The number of days which young stock older than 1 year spends grazing in 2018 (days/year)	89,9
$Q_{grazingdays\ MC}$	The number of days which milk cows spend grazing in 2018 (days/year)	159
W calf	The average weight of a young stock younger than 1 year (calf) (kg)	320
W heifer	The average weight of a young stock older than 1 year (heifer) (kg)	540
W MC	The average weight of a milk cow (kg)	650
%fat	The percentage fat in milk produced by milk cows (%)	4,37
%protein	The percentage protein in milk produced by milk cows (%)	3,56