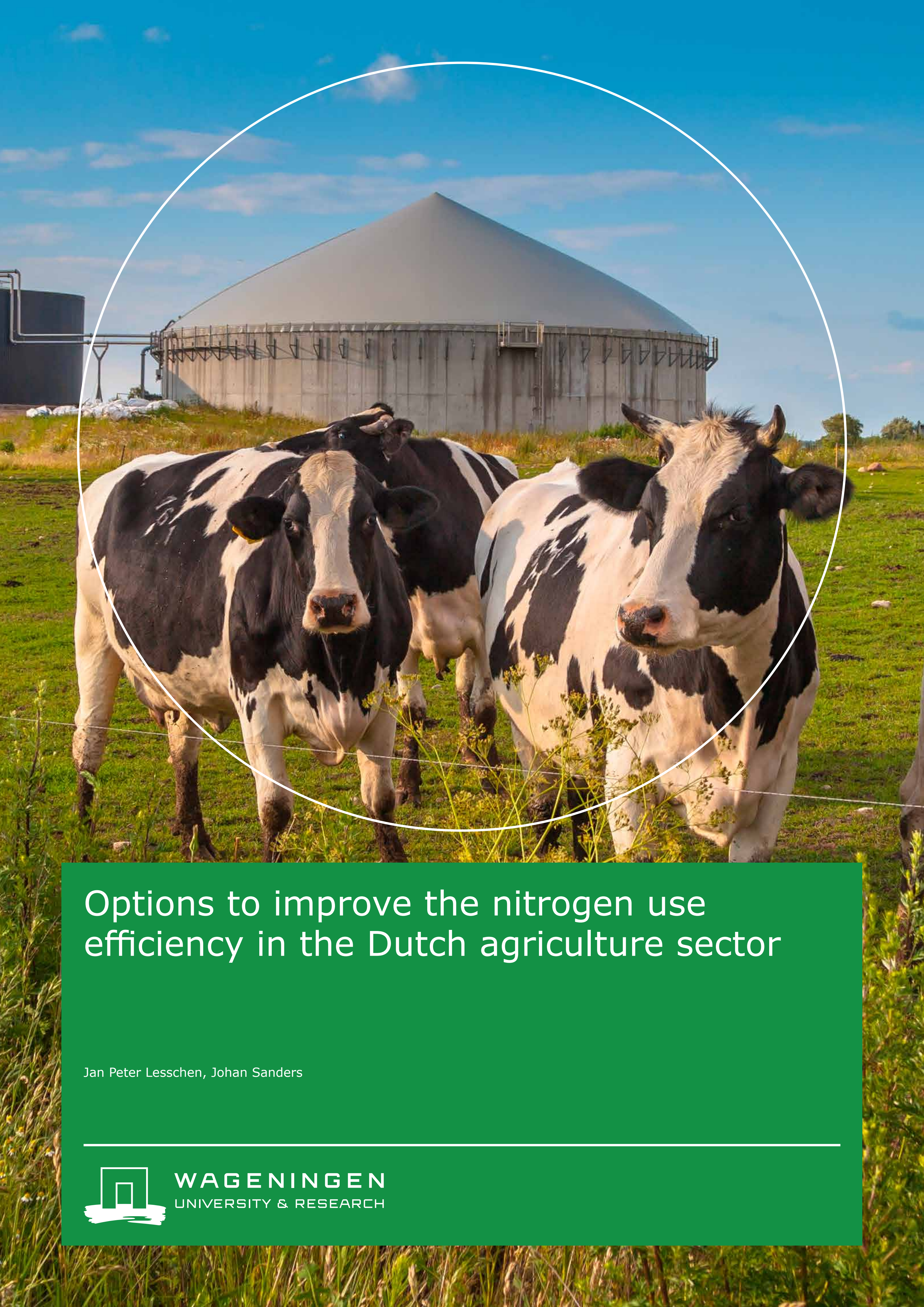

Options to improve the nitrogen use efficiency in the Dutch agriculture sector

Jan Peter Lesschen, Johan Sanders

WAGENINGEN
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This study was performed by Wageningen Environmental Research and Wageningen Food & Biobased Research and was commissioned and financed by STW, as part of the STW protein programme Meer en Beter Eiwit (12640). In addition, funding was received from the EU Horizon 2020 project Nutri2Cycle (Grant Agreement no 773682).

Wageningen Environmental Research
Wageningen, May 2023

Reviewed by:
Gerard Velthof, Senior Researcher (Wageningen Environmental Research)

Approved for publication:
Gert Jan Reinds, Sustainable Soil Management

Report 3258
ISSN 1566-7197

Lesschen, J.P., J.P.M. Sanders, 2023. *Options to improve the nitrogen use efficiency in the Dutch agriculture sector.* Wageningen, Wageningen Environmental Research, Report 3258. 36 pp.; 9 fig.; 4 tab.; 58 ref.

Het doel van deze studie is het kwantificeren van stikstofstromen en stikstof-efficiëntie (NUE) van de Nederlandse landbouw en het verkennen van opties om deze efficiëntie te verhogen. Opties voor verbetering zijn gerelateerd aan i) vermindering van kunstmestgebruik, ii) vermindering van de import van veevoer en iii) vermindering van de N emissies. Een inschatting van de impact van deze opties is gemaakt voor 2030 en 2040. De huidige NUE voor de teelt van gewassen is 58% en voor de veehouderij 30%. De resultaten laten zien dat toepassing van de opties kunnen leiden tot een besparing van 97 kton N in 2030 en tot 209 kton N in 2040. Hiermee neemt de NUE van de Nederlandse landbouw toe van 40% in 2020 tot 52% in 2040. Een groot deel van de N besparing is gerelateerd aan minder kunstmestgebruik, waarbij toepassing van grasklaver de grootste potentie heeft. De studie laat zien dat er in de Nederlandse landbouw nog voldoende potentie is voor verdere verbetering van de NUE, wat bijdraagt aan het sluiten van kringlopen en vermindering van N emissies.

The aim of this study is to quantify the N flows and nitrogen use efficiency (NUE) in Dutch agriculture and to assess options to improve this efficiency. Improvement options related to i) reduced mineral N fertilizer use, ii) reduced feed import and iii) reduced N emissions were identified and their impact was estimated for 2030 and 2040. Current NUE of the crop system is 58%, whereas in the NUE of the livestock system 30%. The results show that the improvement options could lead to N saving of 97 kton by 2030 and up to 209 kton N by 2040. This would increase the NUE of Dutch agriculture from 40% in 2020 to 52% in 2040. Most of the N savings can be obtained by measures that reduce the mineral N fertilizer use, of which the use of clover in grassland is the main option. These findings show that there is still large scope for improvement in NUE in Dutch agriculture, which will reduce the N emissions to the environment and improve nutrient cycling.

Keywords: nitrogen, nitrogen use efficiency, agriculture, technology, emissions

Wageningen Environmental Research Report 3258 | ISSN 1566-7197

Photo cover: Shutterstock

Contents

Verification

Report: 3258
Project number: 5200044084

Wageningen Environmental Research (WENR) values the quality of our end products greatly. A review of the reports on scientific quality by a reviewer is a standard part of our quality policy.

Approved reviewer who stated the appraisal,

position: Senior Researcher

name: Gerard Velthof

date: 24-02-2023

Approved team leader responsible for the contents,

name: Gert Jan Reinds

date: 27-02-2023

Summary

With a growing world population and changing diets, the global demand for animal proteins for human consumption is expected to continue to increase. However, the production of animal proteins has a significant impact on the environment, including expansion of agricultural land, greenhouse gas emissions, eutrophication of surface waters and nutrient imbalances. The nitrogen (N) recovery in animal farming is inherently lower than in crops, with only 10–50% of N in feed being retained in live weight and 5%–40% in the edible weight. Several options consist to improve this efficiency, either by reducing N losses, reducing external N inputs, such as mineral fertilizer, or improve the feed conversion.

In the Netherlands nitrogen and feed use efficiencies have already improved over the last decades. The soil N surplus (N inputs minus crop N uptake) reduced from more than 600 kton N in 1990 to about 270 kton N in 2020. This reduction has mainly be achieved by more strict manure and fertilizer policies. Nevertheless, water and air quality still needs to been improved further in several regions, while climate change mitigation and nature preservation are becoming more important. The aim of this study is to quantify the N flows and nitrogen use efficiency (NUE) in Dutch agriculture and to assess options to improve this efficiency. This study contributed to the overall STW protein programme *Sustainable protein recovery* by providing recommendations for further research on improving protein efficiency.

The analysis of N flows and efficiencies is based on the existing N flow scheme for the EU from Westhoek et al. (2014). For this study we focussed on the Netherlands and used data from the national emission model NEMA, Statistics Netherlands (CBS) and FAOSTAT to quantify N flows for the Dutch agricultural system for the year 2020. The starting point of this study is to maintain the current food consumption and production of proteins, but reduce the external inputs to the system, i.e. mineral fertilizer use and import of feed protein from outside the Netherlands. A range of improvement options were identified and their impact was estimated for 2030 and 2040, where the last one represents the technical potential. The following improvement options were assessed, which were grouped into three main categories:

1. Options to reduce mineral N fertilizer use
   a. Mineral concentrates
   b. Alternative use of poultry manure
   c. Stripping of ammonia during anaerobic digestion
   d. Recycling of human waste as fertilizers
   e. Precision fertilisation
   f. Grass clover
   g. N fixing protein crops
2. Options to reduce import of feed
   a. Biorefinery (grass, crop residues and aquatic biomass)
   b. Higher yielding grass species
   c. Insects for animal feed
   d. Synthetic amino acids in feed
   e. Increase resistance of proteins in cows diets
3. Options to reduce N emissions
   a. Chemical or biological NH_3 scrubbers in animal housing systems
   b. Separated collection of urine and faeces in stables
   c. Acidification of manure storages
   d. Cover crops
   e. Nitrification inhibitors

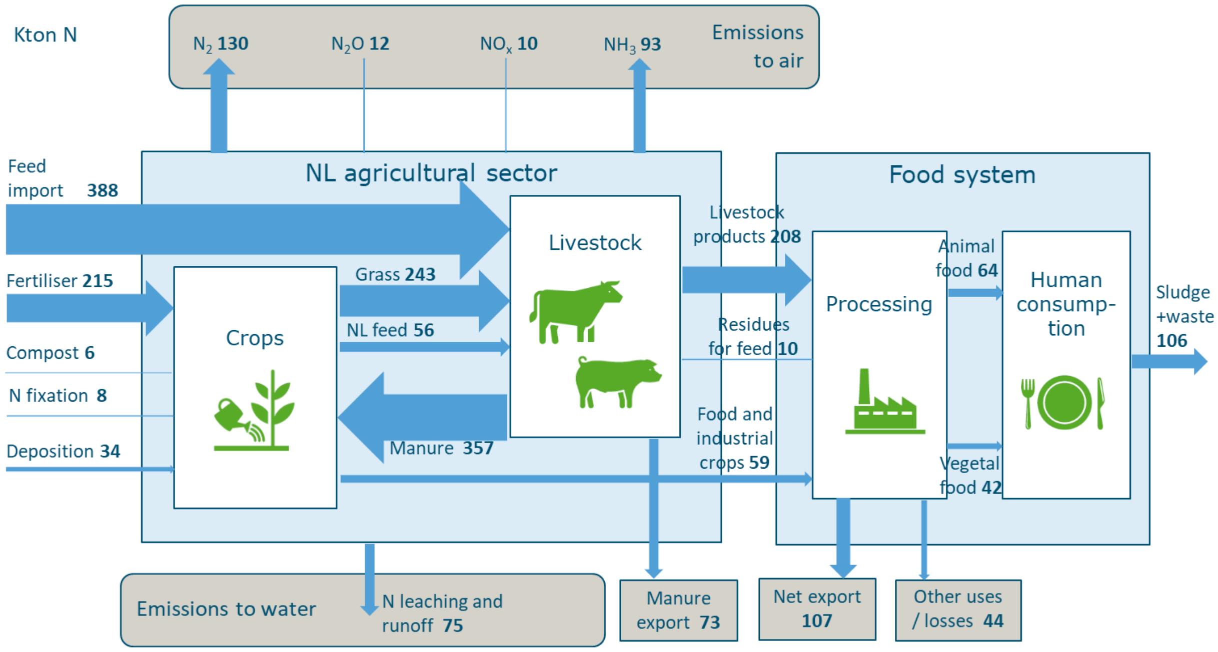

Figure S1 *Nitrogen flows (kton N) in the agricultural and food system in the Netherlands for the year 2020.*

The current N flows in Dutch agriculture show that import of feed and mineral fertilizer use are the two main external sources of N input and gaseous emissions to the environment the main losses (Figure S1). Current NUE of the crop system is 58%, whereas the NUE of the livestock system is only 30%. Our results show that the improvement options could lead to N saving of 97 kton by 2030 and up to 209 kton N by 2040 (Figure S2). This would increase the NUE of Dutch agriculture from 40% in 2020 to 52% in 2040. Most of the N savings can be obtained by measures that reduce the mineral N fertilizer use, of which the use of clover in grassland is the main option. For the short term (2030) options that reduce N emissions and replace mineral fertilizer are most promising, e.g. mineral concentrates, use of grass clover, precision fertilisation and cover crops. On the longer term biorefinery for more efficient use of protein, new sources of local protein (e.g. insects) and stripping of ammonium during anaerobic digestion can contribute most to the further reduction in external N inputs.

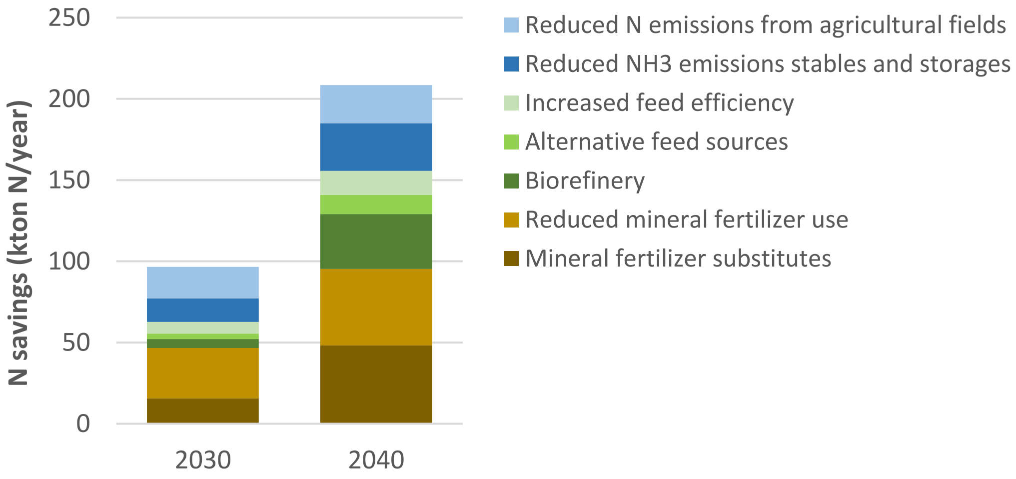

Figure S2 *N savings (kton N) for NUE improvement options in Dutch agriculture compared to 2020, aggregated to main reduction categories.*

These findings show that there is still large scope for improvement in NUE in Dutch agriculture, which will reduce N emissions to the environment and contribute to closing nutrient cycles. However, many of the improvement options are not yet cost-effective or still need to be further developed. This requires an holistic approach, with collaboration and multi-disciplinary research programmes to reduce cost and conflicting regulatory issues.

1 Introduction

1.1 Background

Western diets are characterised by a high intake of animal products. With a growing world population and changing diets, the global demand for animal proteins for human consumption is expected to continue to increase. However, the production of animal proteins has a significant impact on the environment. Livestock production systems have been linked to expansion of agricultural land and associated deforestation, emissions of greenhouse gases, eutrophication of surface waters and nutrient imbalances (Steinfeld et al., 2006). The strong increase of mineral N fertilizer use caused perturbation of the N cycle, which is now considered to have crossed the planetary boundary at global scale (Steffen et al., 2015). Concerns about animal welfare, reactive N and greenhouse gas emissions have stimulated public debate in Europe about eating less meat and dairy products. Changing 'western' diets to diets with less animal protein can have positive outcome for both human health and the environment (Westhoek et al., 2014).

However, also the current production of animal proteins can be made more efficient. N recovery in animal farming is inherently lower than in crops, with only 10–50% of N in feed being retained in live weight and 5%–40% in the edible weight (Figure 1). Several options consist to improve this efficiency, either by reducing N losses, reducing external N inputs, such as mineral fertilizer, or improve the feed conversion.

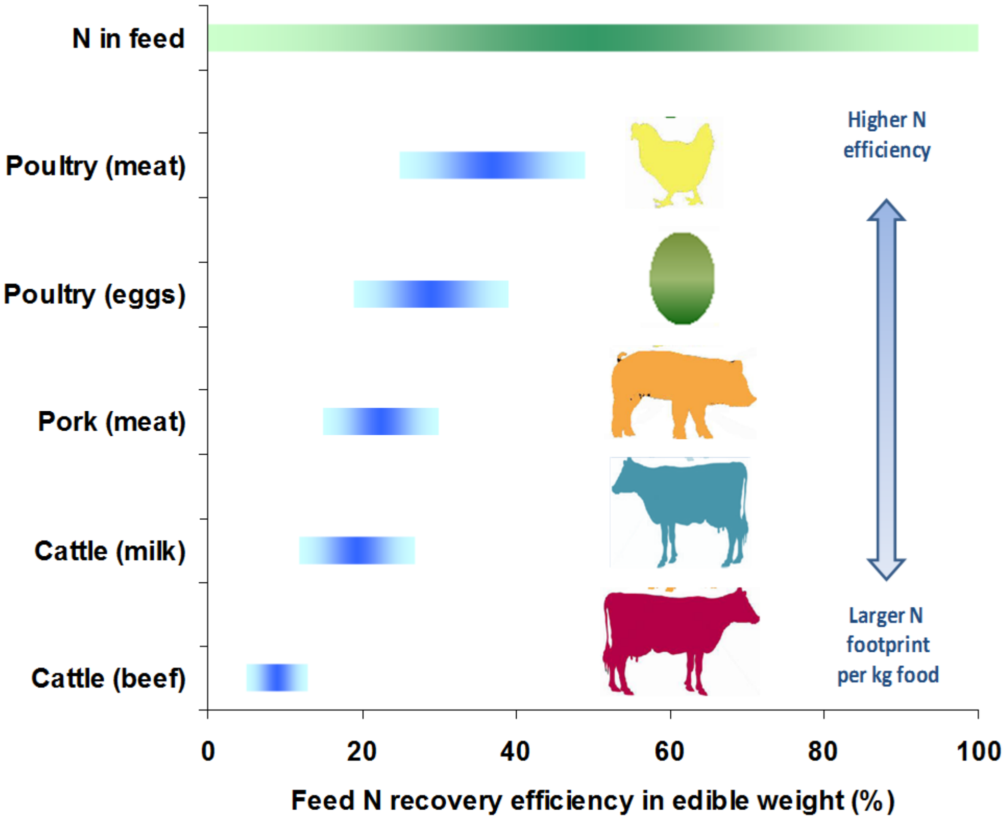

Figure 1 *Range of N recovery efficiencies in farm animal production in Europe (kg N in edible weight per kg N in animal feed). A higher recovery efficiency is indicative of a smaller N footprint (Sutton et al., 2011).*

In the European Union we use about 15 million tonnes of N in the form of fertilizers and protein for animal feed to produce about 2.3 million tonnes of N in food ready for consumption. In other words, we require 6.5 kg of N input to produce 1 kg N in protein on our plates. De facto this number is an underestimation, as for the production of feed for animal protein, there are also losses to the environment. Taking the 15 million tonnes of N input as a reference to feed 510 million people (still including the UK), this means that every citizen had 29 kg of N input available. The use of mineral N fertilizer has caused perturbation of the N cycle, which is now considered to have crossed the planetary boundary at global scale (Steffen et al., 2015). This planetary boundary is estimated at 90 million tonnes of N, which means that in 2050 when the world population has reached about 10 billion people, there will be 9 kg of N for each world citizen. If we want to stay within the planetary boundary, we need to reduce our inputs drastically and if we want to keep the consumption of food protein high as today, the way forward is to improve the Nitrogen Use Efficiency (NUE) by a factor of 3 at least. This can be done by several different actions like reduction of animal protein while increasing plant protein. We might also need to reduce the overall protein intake in Europe which is around 80 g/day on average and in some EU countries well above 100 g/day, while the minimal requirements as defined by WHO are around 50 g/day. This report will not address potential changes in human diets, but will address the question how can we have equal outputs in the Netherlands at lower N inputs and what concrete actions can be taken in the next 10 to 20 years to limit the N losses to the environment.

In the Netherlands the N and feed use efficiencies have already improved over the last decades. The soil N surplus (N inputs minus crop N uptake) reduced from more than 600 kton N in 1990 to about 300 kton N in 2015 (Figure 2). This reduction has mainly been achieved by more strict manure and fertilizer policies, which were primarily aimed at reducing NH_3 emissions and nitrate leaching. Nevertheless, water and air quality still need to improve further in several regions, and also climate change mitigation is becoming more important for the agricultural sector. Therefore further improvement of the N use efficiencies in the agricultural sector is required. Several options exist to improve this efficiency, but a holistic overview of the options and their potential is needed.

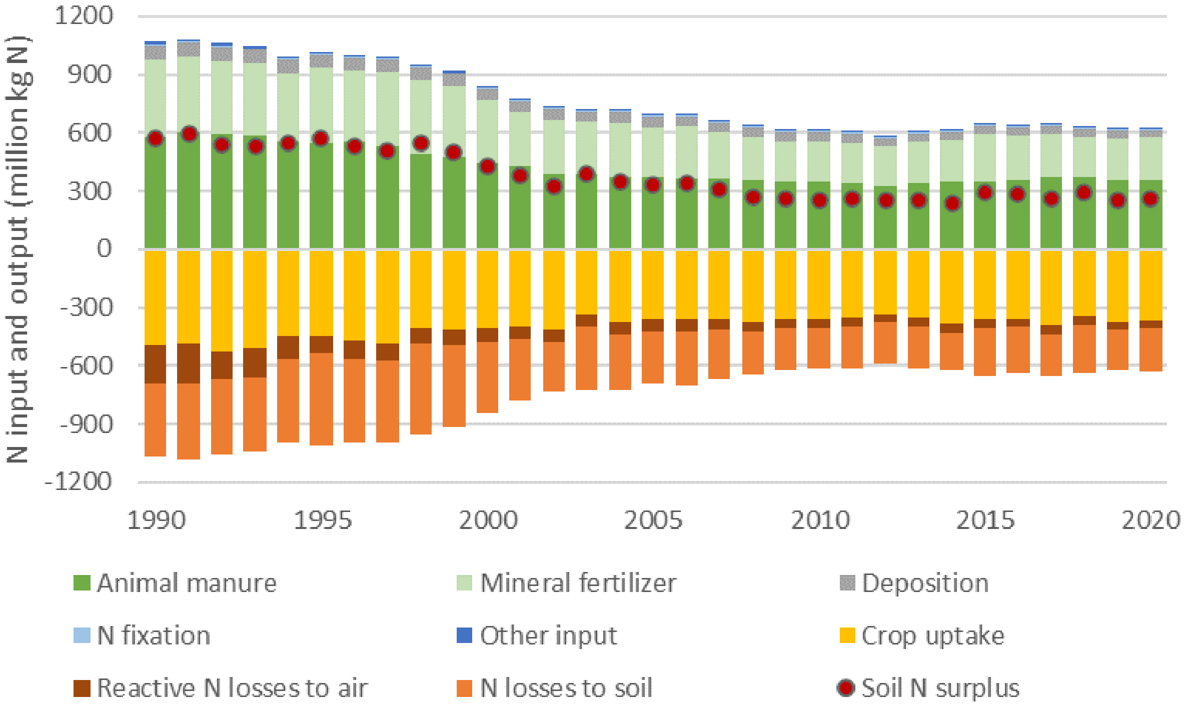

Figure 2 *Development of the N input and output to agricultural soils in the Netherlands (source: CBS, mineral balance agriculture).*

This report is partly based and financed by the STW research program on sustainable protein recovery, which focussed on the development of innovative methods to win proteins from plant materials, micro-algae and insects to meet the growing need for food for humans and livestock. The results of the project where summarised and published in a book (Voudouris et al., 2017) and flyer. This report provides the detailed analysis of N flows and efficiencies in the Netherlands and the impact of improvement options.

1.2 Objective

The aim of study is to quantify the nitrogen flows and nitrogen use efficiency in Dutch agriculture and assess options to improve this efficiency. The starting point of this study is to maintain the current (2020) food consumption and production of proteins, but reduce the external inputs to the system, i.e. mineral fertilizer use and import of proteins from outside the Netherlands and the losses of N. This objective can also be translated in the following research question: How much can we reduce current mineral N fertilizer use and feed import?

1.3 Scope and assumptions

In this report we present a range of options to improve the NUE in Dutch agriculture for both the livestock and arable sectors. However, given the limited budget of this project, we had to make choices and define a clear scope of the study. Therefore we have only assessed technical and management improvement options at the production side and did not consider the consumer side, where changes in diets can have a large effect as well. This means that we assume that the consumption and thus production of proteins will be maintained at the current level.

Second, we limited the scope to the Netherlands. Although many of the agricultural policies are arranged at EU level and also trade of agricultural products and inputs is highly internationally oriented, we decided to focus the calculation of the N flows and impacts of the improvement options on the Netherlands. First of all, because the STW protein project and the involved stakeholders are mainly based in the Netherlands and for them and the Dutch government the Dutch perspective is most useful. Second, because in many aspects Dutch agriculture is atypical for most other regions of the EU, due to a highly productive agriculture, high livestock density and large manure surplus, which leads to different improvement options that are less likely to be implemented in other EU countries with lower livestock densities.

We did not include the economic effects of the improvement options, but the options that were included in the analysis are considered by the authors to be potentially cost-effective on the longer term. Furthermore, some options might be hampered by current (environmental) legislation, but we did not exclude those options beforehand. For the calculation of the N flows a base year of 2020 was used, for which most relevant data was available from the NEMA model. For the NUE improvement options we estimated their potential implementation in 2030 and 2040, for which the last one is considered to be the technical potential.

Finally, all results are expressed in terms of N instead of protein, as N gives a more complete picture of the total chain, with e.g. the inputs of fertilizer and losses due to emissions. However, the results can be easily converted to protein, as for plant based protein a conversion factor of 6.25 * N and for animal based protein 6.38 * N can be used.

2 Methodology

2.1 Approach

The study consisted of two main parts. First the current N flows and nitrogen use efficiencies were determined based on statistical data and model results. Second, NUE improvement options were identified and their potential was assessed. This is further detailed below:

1. Quantification of current N flows and NUE
2. Identification of options to improve NUE
3. Quantification of technical potential for options
4. Estimate potential use in 2030 and 2040

The analysis of N flows and efficiencies is based on the existing N flow scheme for the EU from Westhoek et al. (2014), see Figure 3. This scheme distinguishes the main inputs of N (feed import, fertilizer, N fixation and deposition), the internal flows between the crop and livestock compartments (produced feed and manure), the emissions to the air (NH_3, N_2O, NO_x and N_2) and water (N leaching and runoff) and the interactions with the food sector (produced crop and livestock products and returned processing residues). For this study we focussed on the Netherlands and used the data from the Dutch emission model NEMA in combination with national and international statistics to quantify the different N flows for the Dutch agricultural system.

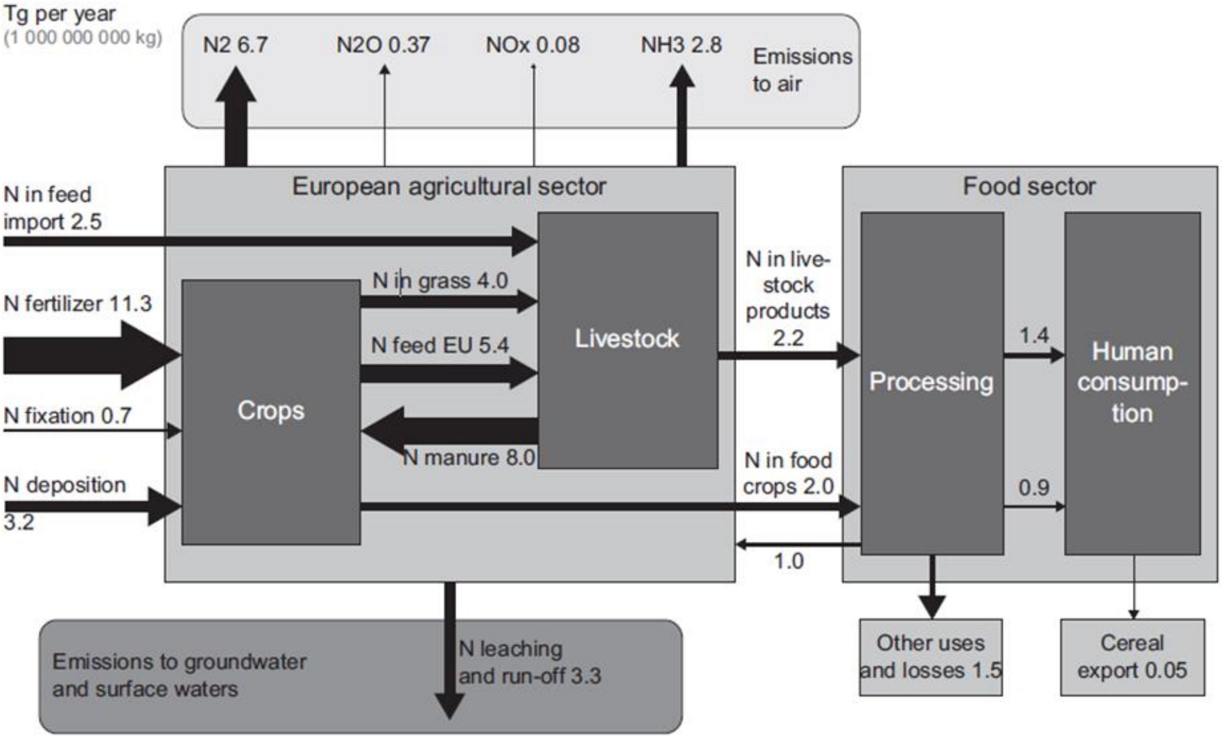

Figure 3 *Nitrogen flows (in Tg yr^{-1}) in the EU agricultural and food systems for 2004 (Westhoek et al., 2014).*

For the identification of the options to improve NUE we clustered them in three main groups, based on the main options to increase the N use efficiency of the system, which are the reduction of external inputs (mineral fertilizer and imported feed) and reduction of losses to the environment. The three main clusters are:

1. Options to reduce N mineral fertilizer
2. Options to reduce import of N in feed
3. Options to reduce N emissions

For each of these clusters we selected promising options, based on the literature (e.g. Hristov et al., 2013), expert knowledge and feedback from stakeholders at the workshop from the STW protein programme. Each of the options was described and a quantitative assessment was made of the potential contribution to increase the nitrogen use efficiency. This assessment was based on simple calculations based on available literature and expert knowledge. This technical potential is assumed to be realistic for 2040, not considering the cost of the measures. Besides, we made an estimate of the more short-term potential for 2030 for each of the options, taking into account costs and current barriers that will limit application of the options.

2.2 Quantification of N flows and NUE

For the quantification of the current N flows, for the year 2020, we used data from the Central Statistical Office (CBS) on the mineral balances for agriculture, which contains information on the N and phosphorus flows in agriculture. For the N emissions the results from the NEMA model (National Emission Model Agriculture) were used. This model is used for the National Emission Ceiling (NEC) and greenhouse gas (UNFCCC) reporting obligations (van Bruggen et al., 2022). In addition data from FAO food balance and trade statistics was used to quantify feed import, food consumption and food export. For the major feed and food items the N content was determined based on data from databases such as FeedPrint[1] and Feedipedia[2] to convert the product data into N flows. Details on the data source for each N flow are provided in Table 1.

Next, the NUE of the Dutch agricultural system was calculated based on the quantified N flows. NUE is defined as the output of N in products divided by the input of N (EUNEP, 2015). The NUE can be defined at different levels. Here we quantified the NUE for crop production, livestock production and the agriculture system.

NUE crop = (Grass + Feed from NL + Food crops) / (Mineral fertilizer + N fixation + N deposition
+ Compost + Manure input)

NUE livestock = Livestock products / (Grass + Feed from NL + Imported feed + Processed feed)

NUE agriculture = (Food crops + Livestock products) / (Mineral fertilizer + N fixation +
Deposition + Compost + N imported feed + Processed feed)

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[1] http://webapplicaties.wur.nl/software/feedprintNL/index.asp

[2] https://www.feedipedia.org/

3 Description of options

3.1 Options to reduce mineral N fertilizer use

3.1.1 Mineral concentrates

Under the Nitrates Directive a maximum amount of animal manure application is allowed in order to prevent too much nutrient leaching to the environment. In countries with a manure surplus, like the Netherlands, the excess manure is therefore exported, whereas mineral fertilizer is used to satisfy the N demand. Processing of manure is considered as an option to increase the nutrient use efficiency of manure. One treatment method is separation of livestock slurry into a solid fraction and a liquid fraction followed by membrane filtration of the liquid fraction. There are four main categories of membrane filtration: reverse osmosis, nanofiltration, ultrafiltration and microfiltration. This results in a concentrated N–potassium (K) solution ("mineral concentrate"), in which most of the N is present as ammonium (Świątczak et al., 2019).

Under the new EU Fertilising Products Regulation (FPR) ((EU) 2019/1009) the sustainable use of fertilisers made from organic waste material will be arranged at EU level. For this the RENURE (REcovered N from manure) criteria[3] have been set, which determine whether a fertilizer can be considered as mineral fertilizer replacement. Although, this still requires a legal status under the Nitrates Directive, it could reduce in the future the need for mineral-based fertilisers. If the properties of the mineral concentrates comply with this regulation, these products would be allowed on top of the animal manure application, and can replace mineral fertilizers.

The production of mineral concentrates already increased from 152 kton in 2016 to 432 kton in 2020. The amount of N in mineral concentrates was about 2.8 kton in 2020 (NCM, 2021). In Lesschen et al. (2011) a range of potential scenarios for large scale use of mineral concentrates has been analysed using the MITERRA-NL model. Scenario S35 seems to be the most relevant, which assumed 50% mineral concentrates from both cattle and pig manure, no export of animal manure, no derogation and decreased N and P excretion. Based on this scenario the potential mineral fertilizer saving was estimated at 10 kton N per year.

3.1.2 Alternative use of poultry manure

Since 2008 about 440 kton of chicken manure is annually being combusted in Moerdijk to generate 245 GWh of electricity. This is about 1/3 of the total amount of poultry manure in the Netherlands. The fresh poultry manure is often dried to 50-60% dry matter by aerating the manure in the stables for a couple of days. The resulting manure contains about 8 kton of N and in order to prevent NOx and N_2O emissions from the burning this N, about an equal amount of N as NH_3 is required in the de-NOx filter[4]. In this way 16 kton N is lost annually.

There are several alternative approaches to optimize the use of the N in the poultry manure. 1) To use the poultry manure directly in agriculture, as it a good fertilizer, especially for organic agriculture (Staps and Nauta, 2011). However, as long as the Netherlands has a manure surplus, this is not the most likely option, as poultry manure is the most suitable manure type for export, due to its high dry matter and phosphate content. 2) Fresh poultry manure can also be used as a substrate in a biogas digestor to generate electricity, see also section 3.1.3. There is no need to dry the manure and in case the manure is transported to the biogas digester within one or two days, only a small amount of NH_3 is emitted. The N is mineralized during fermentation and leads to very high NH_3 concentrations in the digester that inhibit methane formation. The ByoFlex system[5], an NH_3 stripping technology, is able to extract up to 75% of the NH_4, which is in manures about 50% of total N, that is recovered in a strong acid to form ammonium sulphate or ammonium nitrate

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[3] https://publications.jrc.ec.europa.eu/repository/handle/JRC121636

[4] https://www.martechopleidingen.nl/downloads/rookgasreiniging_voorbeeld.pdf

[5] https://byosis.com/systems/byoflex

that can be used as a RENURE mineral fertilizer. In that case the mineral N fertilizer production can be reduced by 3 kton. However, under the current legislation and manure surplus, the digestate that is rich in P still has to be exported. 3) In fresh poultry manure up to 70% of the N is in the form of uric acid that can be extracted and potentially used as a renewable flame retardant. This property has been demonstrated at small scale up to 50% recovery of the uric acid (Hatsuhiko and Shinya, 2006). In all three cases, 8 kton N is no longer required for the de-NOx filter if poultry manure is not burned. For 2030 we assume no potential as the current plant in Moerdijk has licences till that year, but by 2040 the full potential N savings could be obtained.

3.1.3 Stripping of ammonia during anaerobic digestion

During anaerobic digestion of manure to produce biogas, N components are converted to NH_3 to a great extent. At the high pH of 8 at which the methanogenesis takes place, the NH_3/NH_4^+ equilibrium is shifted towards the gaseous NH_3 that has a limited solubility in water. Further increase of the pH by adding $Ca(OH)_2$ or better heating will lower the solubility and the NH_3 can be stripped from the liquid preferably by circulating air through the manure. This air is ‘washed’ by leading it through a vessel with a strong acid like sulphuric acid or nitric acid in which the NH_3 is bound as ammonium salt of these acids that can be used as a fertilizer. During the past 5 years (2016-2021) the technology has reached maturity and is now in operation economically without any requirement for subsidies at various locations in the world. The economics of this technology comes from speeding up the methane formation in the digester, because stripping during the fermentation lowers the NH_3 concentration that is inhibiting the methanogenesis process. The technology can also be applied on municipal wastewater treatments as well.

In practice about 65% of the NH_4 in the substrate can be recovered by stripping[6]. If all cattle and pig slurry would be digested and stripped, the total amount of N in ammonium sulphate produced would be about 110 kton N, based on total amount of N in manure of 340 kton N in manure and 50% mineral NH_4-N in manure. Theoretically the recovery of N can be even higher, as during digestion the NH_4 content will increase to levels where 65-75% of the total N can be stripped. Currently about 5% of the produced manure is processed by anaerobic digestion, mainly pig manure (Vonk et al., 2021). If all these anaerobic digesters in the Netherlands would be equipped with a NH_3 stripper, 5.5 kton N[7] as ammonium sulphate can be produced by 2030. This can replace mineral fertilizer and can be applied on top of the animal manure application limit of 170 kg N/ha, when the use of RENURE products is approved. For 2040 we assume that 60% of all pig manure and 10% of all cattle manure is being digested and stripped, this is about 87 kton N, which would increase the N recovery to 28 kton N. Stripping will also reduce NH_3 emissions, from stable and storage if manure is directly removed to the digester, and from application of the digestate to the field as the NH_4 content is much lower. However, NH_3 emission from application of ammonium sulphate is higher compared to other mineral fertilizers, therefore we did not quantify the possible reduction of NH_3 emissions. With large scale stripping the amount of sulphate might become an issue, as this will lead to soil acidification. However, other types of acids could be used for binding the stripped ammonia in a salt form as well.

3.1.4 Recycling of human waste as fertilizers

CBS (2016) indicates that 89 kton of N ends up in wastewater systems of which 84% (74 kton N) is derived from household, mainly from human excrements, but also some kitchen residues. Of this amount some 17 kton N ends up in the wastewater sludge, while the rest of the N in the sewage (57 kton) goes to the air as N_2 after conversion steps as nitrification and denitrification during the waste water treatment. At several places in Europe research has been done on how to collect N and P already in a concentrated way from the toilets in houses. Two approaches have been studied: the first is to collect the urine with no mix toilets and collect this urine in the neighbourhood and transport it to agricultural fields as fertilizer. The other approach is to collect all the excrements together and digest these in an anaerobic fermentor to obtain biogas and later transport the minerals for use in agriculture. Lack of infrastructure and the cost to implement these together with the presence of medicine residues has so far prohibited their implementation. However, new technologies are being developed that can recover N even at quite low concentrations. Therefore we assume

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[6] https://byosis.com/systems/byoflex

[7] 340 kton N manure * 5% implementation * 65% recovery.

that by 2040 about 10% of the N in wastewater can be recovered and used as fertilizer, which can reduce the mineral fertilizer input by 5.7 kton N.

In the Netherlands the application of sludge in agriculture is not allowed because of contamination with heavy metals and pharmaceutical residues. Nowadays 90% of all sludge is combusted to produce electricity or cement[8]. As in the case of poultry manure also a phosphate and potassium rich ash remains, which can be used as fertilizer after further processing. The combusted sludge contained some 17 kton of N and as a consequence the same amount of NH_3 or urea is required for the de-NO_X filter. As for the poultry manure, the sludge could also be used to produce biogas after which most of the NH_3 can be stripped without the need to have a de-NO_X filter, resulting in a potential reduction of N requirement of 12.8 kton N[9]. If the digestion and N stripping for sludge would work, it could be implemented relatively fast, as there are only limited number wastewater plants. We assume 30% could be treated by 2030 and 60% by 2040.

3.1.5 Precision fertilisation

Precision fertilisation, a precision agriculture technology, adapts the fertiliser use based on the crop nutrient requirements. This can reduce the fertilizer inputs and also reduce the N losses. Precision fertilisation combines GPS, proximal or remote sensors, and computers on agricultural machinery and tractors in order to observe, measure and respond to spatial and temporal variation in crop nutrient requirements (Zarco-Tejada et al., 2014). This technique is also called variable rate N-application, which optimises the N application by considering the in-field variation in crop nutrient needs. Precision fertilisation follows the 4R Nutrient Stewardship: applying the right fertiliser, in the right rate, at the right time, and at the right place.

Data from farm trials show a large spread in the fertilizer savings if precision fertilisation is used, with mainly reductions in fertilizer use, but sometimes also an increase. At least there is consistency among authors about the increased N use efficiency and reduced losses to the environment due to variable rate application. Based on a European survey amongst 540 arable farmers, an average savings of N fertilizer of 8% was observed as a result of the adoption of variable rate N-application. Besides on average an increase in the crop yield was observed (Barnes et al., 2017). Due to lack of data of the reduction potential at national scale for the Netherlands, we have assumed the same reduction percentage. Given the reduction of allowed fertilizer and manure application rates due to more strict manure policies, the potential fertilizer savings will have decreased over time, and therefore a much higher saving is probably not realistic. Most experience with precision fertilisation is obtained in arable cropping systems, but there is also potential for grassland. Machine guidance with GPS can prevent duplication of fertilizer spreading, and variable rate N-application can also improve the N use efficiency in grassland. The survey from Barnes et al. (2017) did not include grassland, therefore we estimated that in grassland the potential is half of that in arable cropping. This results in a potential reduction in mineral fertilizer use of 6%, which is about 14 kton N per year.

3.1.6 Grass clover

Legumes are a group of plant species that can fixate N from the air to produce plant protein and other N-components. Examples are clover, alfalfa, soy and many other species. The energy that is required to bind the N from the air is generated by photosynthesis and in this way no natural gas is required as in the large fertilizer factories. Since the bacteria that bind the N are located on the roots of these plants, more than 95% of the bound N ends up in the N-products in the plants (Carlsson and Huss-Danell, 2014). Therefore at the most 5% of the bound N leaks to the soil water or is emitted as ammonia as compared to about 40% in case of grassland but as high as 75% in case of a vegetable crop like spinach.

Legumes can also be grown in mixed culture with non-leguminous plants, often benefitting from the high crop yields of these latter such as perennial grasses and benefitting from the N fixating properties of the legumes. Grace et al. (2018) showed that mixed species crops of 6 or even 9 different species can give equal or better plant protein yields per hectare with inputs of 1/3 or less of the traditional N fertilization application. This so-called multi-species sward grassland combines normal grass with legumes and herbs.

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[8] https://www.clo.nl/indicatoren/nl0154-afzet-van-zuiveringsslib-naar-bestemming

[9] 17 kton N in sludge * 75% N removal efficiency = 12.8 kton N saving.

Moloney et al. (2020) showed that in Ireland this multi-species sward without any fertilizer gift, produces similar outputs as traditional grassland to which 300 kg/ha N fertilizer is applied.

In the Netherlands the largest potential for N fixation is in the dairy sector, where clover can be used in combination with grass species, which will reduce the need for mineral N fertilizer. If the N fertilization is high, the clover will not grow well and disappear from the sward over time. Therefore clover works well in temporary grassland and more extensive permanent grassland. According to the fertilization advice[10], with clover only N fertilization of 30-80 kg N/ha is required for the first grass cut. However, farmers will still apply most of the manure with a maximum of 170 kg N/ha. Therefore we assume that only the mineral fertilizer is replaced, which is about 115 kg N/ha (Source: Agrimatie). Dry matter yields of grass clover are often a bit lower compared to grass in Dutch conditions, but milk production can sometimes remain the same. The current area of grass clover is unknown, but based on the area of organic grassland[11], about 3.5%, we estimate the current area at 36 kha. If we assume grass clover would be used in all temporary grassland and 25% of the permanent grassland, this could reduce the annual N fertilizer need by 57 kton, this is based on an area of 212 kha temporary grassland and 180 kha permanent grassland and corrected for 36 kha of current grass clover and an average N fertilizer reduction of 115 kg N/ha. We assumed that by 2030 50% of this potential is used and by 2040 90%. Besides the N fertilizer saving, the clover can also increase the protein content of the silage, which could reduce the need for protein rich concentrate. However, as this is quite uncertain due to lack of data, we did not quantify this potential reduction of feed import.

3.1.7 N fixing protein crops

With the protein strategy the EU aims to increase the cultivation of protein crops in Europe and also the Dutch arable sector would like to increase the area of protein crops. The current area of N fixing crops was in 2020 about 21 kha. However, in the highly intensive Dutch agriculture, most protein crops will not be competitive to other crops and with low cost imported soybean, which makes a large share of N fixing arable crops unlikely. Faba beans (*veldbonen*) are the most promising N fixing crop, as crop yields are higher compared to other protein crops. Also feed crops like alfalfa (*luzerne*) could be included in an arable crop rotation. According to the national protein strategy (LNV, 2020), there would be space for 100-125 kha of N fixing crops in Dutch arable agriculture. However, a more realistic estimate would be an increase to 50 kha, based on an average N fixation of 150 kg N/ha, the mineral N fertilizer use could be reduced by 4.5 kton.

3.2 Options to reduce import of feed

3.2.1 Biorefinery

Grass refinery
Biorefinery is the separation of biomass into different useful components. In the case of grass refinery often a liquid component high in protein and a solid component high in fibres is produced. The liquid fraction can be further treated to separate protein and minerals. Biorefinery of grass in the Netherlands and in Denmark has shown that the yield of animal protein that can be produced on this biorefined grass can be 50% higher as compared with unrefined (ensiled) grass (Pijlman et al., 2018, resulting in manure with 30% lower N and phosphorus contents. The amount of milk production remains the same with the refined grass, while in addition pigs or poultry can be fed on the protein rich component. This can be explained by the fact that a cow can only benefit from about 75% of the grass, the other part will leave their body as manure without being digested. The biorefinery process unlocks almost 100% of the grass cells, and thereby the grass proteins become available as animal feed (Koopmans personal communication, 2022). In an Irish study with press cake from grass biorefinery the protein content in cattle feed was reduced from 18% to 15,2% while the milk yield was the same as the control. The N excreted was 17% lower as compared with the control experiment (Serra et al., 2023).

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[10] https://www.verantwoordeveehouderij.nl/nl/verantwoorde-veehouderij-2/show-5/na-eerste-snede-geen-stikstofbemesting-nodig-voor-grasklaverpercelen.htm

[11] https://www.agrimatie.nl/themaResultaat.aspx?subpubID=2232&sectorID=2243&themaID=2267&indicatorID=2013

Another reason that contributes to the higher protein use efficiency, is because grass protein is fractionated over a fraction with fibres and moreover insoluble grass protein that has a significant higher proportion of 'resistant' protein. Since the composition of the grass protein consists of a high level of essential amino acids, the cow will fully benefit from these amino acids. Another protein fraction contains the soluble part of the grass protein, which therefore is well digestible for pigs and poultry. In addition, during the ensilage process about 15-20% of the grass is lost due to field losses during drying of the grass and leakage.

The area of grassland in the Netherlands is about 950 kha, with an average yield of 10 ton DM per ha[12]. The protein content in grass varies over the season, but is on average about 18%. This is 1.8 ton protein per ha (288 kg N/ha), which results in a total protein production of 1710 kton, equal to 274 kton of N. With grass refinery per ha of grassland the same amount of cows can be fed and in addition 45% of the protein can become available for pig or chicken feed (Sanders et al., 2021), which would be 130 kg N/ha. Not all this grass can be refined, as part will be used for grazing and hay, and also the logistics for large scale refinery will take time to develop. Often new biorefinery technology for specific raw materials have to be developed and major contributions are not expected before 2030 because the development of technical processes usually take at least 10 years. However for the biorefining of a variety of leafy materials we consider this to happen before 2025 since the technology for grass is on the verge of commercialisation in the Netherlands and Denmark. For 2030 we assume grass refinery will be possible at 30 kha, resulting in 3.9 kton N of imported feed that can be replaced. For 2040 we assume that 20% of all grassland can be refined, this would be about 190 kha of grassland, which would provide 24.7 kton N as feed for pigs and poultry.

Crop residues

The biorefinery technology, as described above for grass, can also be used for leafy crop residues such as beet leaves, carrot leaves and vegetable residues, but also for cover crops. The Beet Sugar Company in the Netherlands has taken the initiative to isolate from beet leaves, proteins with high functionality in food applications for similar markets as the Dutch potato starch industry started to develop some 20 years ago. About 5% of the potato protein that is collected from a former process residue is now successfully marketed in these high-end applications, the other 95% of the (residual) proteins find their application in the animal feed industry.

In the Netherlands sugar beet is cultivated on about 80 kha. Apart from 80-100 tonnes of fresh beets, about 45 tonnes of leaves are produced corresponding to about 5 tonnes of dry matter. Most of these leaves are left on the field after harvesting the beets in autumn and within weeks this protein is degraded and converted to ammonia and nitrate and up to 75% of the N is lost before the next crop is seeded in spring (de Ruijter and Smit, 2007). At least new N fertilizer is required to compensate for these N losses. In case all leaves would be collected and used for biorefinery, about 6.6 kton of N (80 kha, 110 kg N per ha (de Ruijter et al., 2009) and 75% N losses) could be saved and used for other applications or returned to the field as digestate during spring. For some of the vegetable, with many leaf residues, refinery could also be an option, here we assumed 20 kha (about 25% of the cultivated vegetable area) and 80 kg N/ha in residues, which results in a total of 1.2 kton N. As scaling up of the refinery technology will require time, we assumed that by 2030 10% of this sugar beet and vegetable leaves are used, and in 2040 50%. One should take care to supply a source of organic material back to the fields either that results from the biorefinery or from manure or from another agricultural residue.

Aquatic biomass

Aquatic biomass is potentially a new source for protein that is currently hardly used. A distinction can be made between marine biomass sources, mainly seaweed, and biomass from freshwater, like duckweed and azolla.

Seaweed

For seaweed a good estimate of the potential production is still lacking, previous estimates of yields and production volumes, such as Van Hal et al. (2014), seem to be too optimistic. A recent literature study (Mes et al., 2021) assessed the future for protein from North Sea seaweed. One of the applications is the use of protein from seaweed as animal feed to replace soybean. They used the following assumptions: an area of 145 km^2 where seaweed (*Saccharina atissimi*) can be grown, which can produce up to 15 ton DM/ha, but

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[12] https://www.agrimatie.nl/PublicatiePage.aspx?subpubID=7352&themaID=2754&sectorID=3534

more realistic is 10 ton DM/ha. Seaweed would only be used as protein source after biorefinery, as otherwise the cost of transport due to the high water content (dry matter content is only 10-15%) would be too high. The protein content of seaweed is variable, ranging between 7 and 27% depending on the species, whereas the protein content also varies during the season. Based on an average protein content of 15%, the potential production would be about 22 kton protein, which is 3.5 kton N.

However, Mes et al. (2021) conclude that the offshore production cost for cultivated seaweed is too high to compete with other protein feed. This is also in line with the economic analysis by Jansen et al. (2019), who showed that significant cost reductions are possible for North Sea seaweed cultivation, but the resulting cost price of about €1200 per ton DM would be too high for protein extraction for feed. Also the extraction of protein is more complicated compared to terrestrial biomass because of the high water content and minerals in the seaweed. Offshore seaweed cultivation seems only possible for more high-end purposes, like food ingredients or for specific components that are extracted from seaweed. Therefore we assume no potential for 2030 and 3.5 kton N for 2040 in case it would become cost-effective.

Duckweed and Azolla

For fresh water biomass the cultivation might be easier to organise, but the potential area for its cultivation is limited. Duckweed and Azolla are the main species that can be used for protein production, as these have a high protein content, for duckweed about 30% (25-39%) and Azolla about 20% (14-28%) and they have a good composition of amino acids. The benefit of azolla is that it lives in symbiosis with cyanobacteria, which can fix N from the air if the N availability in water is low. The potential dry matter production per ha under controlled circumstances, e.g. in greenhouses, is 20-25 ton/ha, but will be lower under field conditions, e.g. in lakes or ditches.

If we assume an area of about 1000 ha of greenhouses (~10% of total greenhouse area in the Netherlands), 23 kton dry matter of aquatic biomass can be produced, which represents 900 ton N. For production of aquatic biomass (duckweed and/or azolla) under field conditions, a lower yield is assumed of 10 ton DM/ha. If an area of 2000 ha would be used, this could provide 20 kton dry matter, which is about 800 ton N. This protein production is under conditions that the growth of the aquatic plants is based on domestic animal manure and wastewater as the N source. The combined potential for protein production from aquatic biomass would be 1.7 kton N. A higher potential is unlikely, given the cost and problems with large scale outdoor production. For 2030 we assume that 50% of this potential might be feasible.

3.2.2 Higher yielding grass species

The most common grass species in the Netherlands for agriculture is ryegrass. However, other grass species are available as well, and some can have higher yields. A potential candidate species is *Festuca arundinacea* (Rietzwenkgras in Dutch). The yield can be 16-20 ton DM/ha in the Netherlands. In Denmark this grass species is also used, and experimental research shows that even while 500 kg/ha N fertilizer is applied the N losses to the soil are as low as 20 kg/ha (Manevski et al., 2018). This is probably because Festuca is a deep rooting species, which can use N more efficiently. The deep rooting is also beneficial for soil carbon sequestration. The crop can be included in rotation with arable crops, e.g. grown for three years.

Therefore it seems most promising to use this species in rotational / temporary grassland. The total temporary grassland area is currently about 200 kha. Assuming that Festuca will be grown on 25% of this area, this would be 50 kha. Current average grassland yield is about 10 ton DM/ha and 1.7 ton of protein/ha or 270 kg N/ha with an estimated N Use Efficiency of 75%. If we use an average yield for Festuca of 18 ton DM/ha, this could result in a grass production of 900 kton with 160 kton of protein and 25 kton of N in plant protein. With an N use efficiency of 90% (Chen et al., 2022), the additional amount of protein produced with the same N inputs would be 335 kg per ha, which is for 50 kha 2.7 kton N more compared to ryegrass. This amount could reduce the import of feed or less ha would be required to produce the same amount of grass.

Figure 4 *Festuca arundinacea.*

3.2.3 Insects for animal feed

The animal feed industry is interested in alternative sources of protein that can reduce the environmental impact of feed production and increase circularity. Research has shown that the nutritional value of insects is at least comparable with the nutritional value of soya beans and fish meal products. Feed from insects can play a major role in making the food chain circular, as insects can be grown on by-products and residual flows from the agrifood sector and on livestock manure. Insects have a much higher feed conversion ratio compared to other farm animals, e.g. black soldier fly larvae are able to convert 43-55% of dietary protein into edible biomass (Oonincx et al., 2015). The main gain in N use efficiency is obtained when insects are reared based on waste streams that are currently not being used for animal feed. Although insects can be reared on manure, the efficiency is much lower (Bosch et al., 2019) and less desired from a food safety perspective. The use of insects in feed for fish farming has been permitted in Europe since 2017. In August 2021, a legislative change was approved that also permits the feeding of processed insect proteins to pigs and poultry.

The expected production of insects in Europe for 2019 is estimated to be around 50,000 tonnes live weight. No study is available that has estimated the potential size of the market of insects for animal feed. So far the production is limited, but with the new legislation the scaling up might go fast. The long-term development is depending on the cost-efficiency of the production process, the market demand, the developments of other alternative protein sources and the potential role of insects in the circular economy (Raad voor dieraangelegenheden, 2018). The crude protein content of insects is about 40-60% and the nutritional value can be equal to soybean meal. Depending on the animal species it can replace 25-100% of the soybean in the animal diet (Makkar et al., 2014). However, as the amount of unused, but allowed, waste streams is limited in the Netherlands, the potential of this option to replace soybean is limited.

Based on data from Nevedi, the Dutch association of feed producers, the total amount of soy used for feed is about 1.8 million tons per year, of which about 800 kton is used for poultry and 500 kton for pigs. We assume that 3% of the soybean in pig and poultry diets will be replaced by insect feed by 2030, extrapolated based on Hoek et al. (2022), and by 2040 this has increased to 10%. One ton of soybean meal contains about 0.45 ton of protein, which is 0.07 ton of N. This means that the N import from soybean feed can be reduced by 2.7 kton N in 2030 and 9.1 kton in 2040.

3.2.4 Synthetic amino acids in feed

The total protein use in compound feed for monogastrics is estimated at 18 million ton protein in the EU (FEFAC). Since proteins consist of 20 different building blocks, the amino acids, not all of each amino acid is present in the right abundance as compared to the other amino acids. For the so called non-essential amino acids a too low concentration would not be a problem since the human and animal body can synthesise all of the eleven non-essential amino acids. However, if one of the essential amino acids is limiting, this results in an inefficient use of all of the other amino acids that are available at higher concentrations. A strategy that has already been followed for the past 40 years is to add amino acids like lysine, methionine and threonine to animal feed. Lysine, These are produced at large scale worldwide (each by millions of tonnes annually) by fermentation using sugar and ammonia with at least 90% use efficiency. This has resulted in a lower requirement for protein in livestock diets in an economic way for these three amino acids. If the other essential amino acids would be available under economic conditions, another 30% of the protein intake from compound feed, being 9 million tonnes, could be replaced by the most limiting synthetic amino acids (Molist et al., 2016). The amount of these essential amino acids could be low as 3.8 Mton amino acids in order to compensate for the 9 Mton of protein.

This is illustrated in Figure 5, which shows on the left the presence of the 20 amino acids expressed as the fraction of the required amount. Methionine (Met) as an example is the most limited and as a consequence all of the other 19 amino acids in the feed protein are overdosed and wasted. If the limiting amino acids are supplemented by free amino acids, as in the right picture, the animal can benefit from all amino acids supplied in the original feed protein. For increasing the amount amino acids, cost reduction of amino acids like leucine, isoleucine, valine, phenylalanine are essential, which requires further genetic improvement of existing production strains that have successfully been followed for the amino acids that are already on the market.

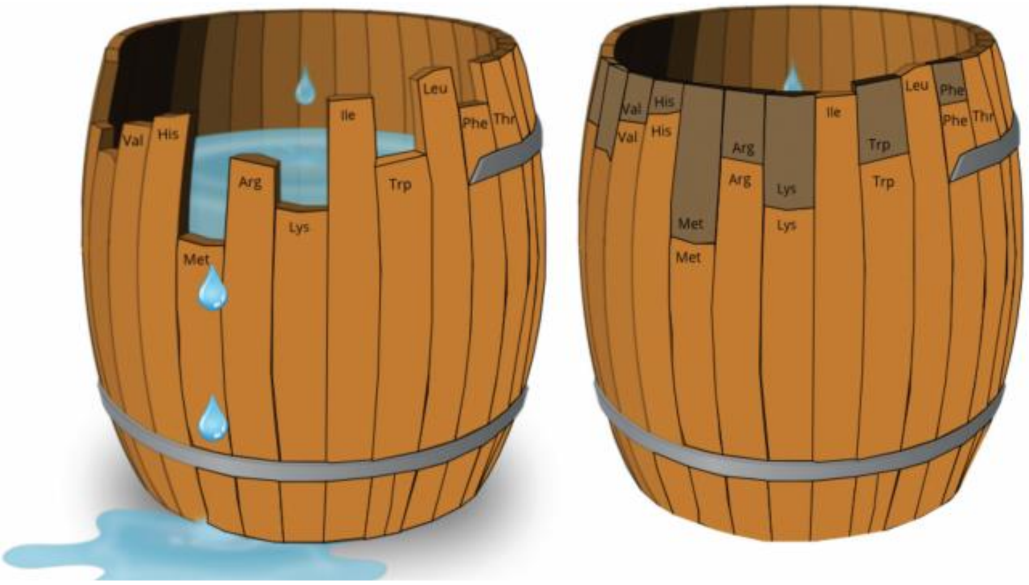

Figure 5 *Schematic illustration of complementary proteins by use of the Liebig barrel (FEFANA, 2014).*

For the Netherlands the total compound feed use for monogastrics (pigs and poultry) is estimated at 7 Mton[13] with an average protein content of 17% being 1,2 M ton protein which contains 190 kton N. About 140 kton N is excreted, of which 88 kton is in pig manure[14]. According to Schothorst Feed Research[15] about 10-12% of the amount of N in pig manure can be reduced after addition of the other essential amino acids, which would be a reduction of 9-11 kton N in compound feed. We assume that in 2030 25% of this potential is used, and 50% by 2040.

3.2.5 Increase resistance of proteins in cows diets

The Dutch cows consume about 2600 kton of protein annually of which just about 600 kton end up in milk and meat (CBS data), a conversion of less than 25%. Part of this low digestibility can be overcome by

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[13] https://nevedi.nl/diervoer-item/feiten-en-cijfers/mengvoerafzet/
[14] https://www.cbs.nl/nl-nl/nieuws/2022/07/minder-stikstof-en-fosfaat-in-dierlijke-mest
[15] Bonekamp in Boerderij 107(2022) No 46, pp 40-43.

unlocking the forage grass in the cows diets as has been mentioned in 3.2.1. Bannink (personal communication, 2023) has shown that protein content can be lowered to 15% without lowering the milk yield by using unlocked grass from the grass biorefinery. For cows the application of essential amino acids in the diet can also contribute in lowering the nitrogen intake as we have seen in 3.2.4 for pigs. However these amino acids have to bypass the rumen in order to be effective. Inclusion of rumen bypass lysine and methionine and increasing digestibility of grass proteins could reduce the protein content even below 15% without reduction of the milk yield (Lee et al., 2012).

The microbial population in the rumen degrades proteins down to amino acids and even to smaller catabolites. At the expense of biological energy, the microbial populations growths and forms microbial proteins that further down the intestinal tract of the cow are digested and taken up in the blood stream. This process makes the cow unique because in this way all kinds of low grade protein sources can be converted to useful proteins to produce milk and meat.

However, Dijkstra et al. (2013) showed that part of the fed proteins are converted to microbial products that are not digestible as proteins or are components such as nucleic acids from which the cow has no benefit. Part of the proteins in the diet are so-called ‘resistant’. These pass the rumen intact and are digested only later in the digestive tract. The cow does not need to invest energy in rebuilding proteins, but more important is that when these resistant proteins contain high proportion of essential amino acids, the cow can, without cost of energy, benefit from these essential amino acids and requires less protein intake in the end. The resistance of proteins was traditionally increased by a formaldehyde treatment. Since this is no longer allowed by European legislation other methods have been developed among which the heating of proteins in the presence of the sugar xylose.

Combining these feed adaptations will probably result in feed that can be fed to cows under most conditions at protein levels lower than 15%, which can reduce the N excretion per litre of milk up to 30%. If by increasing resistance for part of the protein in the diet no longer 17.2% of the dry matter intake is required in the form of protein, but only 15.2%, a feed intake of 2300 kton of protein would result in the same 600 kton milk and meat protein as is now the case based on a feed protein intake of 2600 kton (Serra et al 2023). This reduces the protein need potentially with at least 300 kton, equivalent to 48 kton of N. We assumed that by 2030 10% of this potential is possible, increasing to 25% by 2040, which is 5 and 12 kton N respectively.

3.3 Options to reduce N emissions

3.3.1 Chemical or biological NH_3 scrubbers in animal housing systems

Air scrubbing is a technique used to remove ammonia (NH_3) from the air through forced ventilation in animal housing. There are two methods of air scrubbing, the chemical and biological scrubbers, which have different removal efficiencies. In the chemical scrubber the air is going through a solution with an acid. If NH_3 is absorbed onto sulphuric acid solution (H2SO4) ammonium sulphate ((NH4)2SO4) will be formed, whereas the use of nitric acid (HNO3) as a scrubbing agent would result in ammonium nitrate (NH4NO3) solution. The chemical scrubber can remove up to 70-90% of the NH3 present in the air. In a biological scrubber micro-organisms (mainly bacteria) are used to remove ammonia, mainly by converting it to nitrite or nitrate, which is removed with the water (spuiwater). These systems have a maximum efficiency of 70%. These scrubbers are mainly used for pig and poultry housing facilities, as cattle stables are often open air systems, although new systems are being developed that could also reduce ammonia emissions from these open cattle stables. Air scrubbers can be very effective, but the cost associated with its implementation is one of the disadvantages.

In the Netherlands the decision on low emission housing (*Besluit emissiearme huisvesting*) determines that animal housing should be low emissions according to the available low emission housing systems. All new stables should have an emission that is lower than the maximum allowed emission. A large part of the pig farms are making use of air scrubbers or other low emission stable techniques. For pig farms more than 80% of the stables were low emission housing systems in 2018, whereas in poultry only a small part of the housing systems is making use of air scrubbers and other housing systems are preferred (Vonk et al., 2020). Melse et al. (2019) showed that in practice the effectiveness of combi scrubbers is often lower than expected. Given the preference to reduce ammonia emissions at the source, instead of using ‘end of pipe’ solutions such as air scrubbers, the additional potential for ammonia reduction from air scrubbers is low. The current NH_3 emission from housing and storage systems is estimated at 58 kton N (van Bruggen et al., 2022). Based on Groenestein et al. (2019) an emission reduction of 4.4 kton N in 2030 is estimated related to measures that include air scrubbers in poultry and cattle housing systems.

3.3.2 Separated collection of urine and faeces in stables

Animal housing is the largest source of NH_3 emissions in agriculture, of which the dairy sector contributes most (28 kton NH_3, source Agrimatie, 2020). Current legislation already obliges farmers to use low emission stables when stables are constructed or renovated. The emissions limits become lower over time, which stimulates the development of new stable systems. Currently the use of low emission stables is low in the dairy sector, about 20% in 2020 (Vonk et al., 2021). Separation of urine and faeces at the source is a good option to reduce NH_3 emissions in cattle stables. The numerous micro-organisms in faeces of pigs and cattle are responsible for the fast breakdown of urea to ammonia and CO_2 through the enzyme urease. During the first days of storage in manure cellars the pH goes up by continuing fermentation processes. This higher pH makes NH_3 more volatile, which increases NH_3 emissions from manure storage as well as during the application of manure and digestates to the agricultural fields. New stable floor design such as the TRAC system[16] aim at a fast separation of urine and faeces. The urine flows to a collection tank from the shallow floor of the animal house while the faeces is collected by regular scraping the floor. Still there is some contact between the urine and the faeces so urease will degrade urea probably slower than in mixed storage conditions.

The Dutch company Hanskamp has developed the ‘Cow toilet’ that can collect about 40% of the cow’s urine which can be stored separate from the faeces during the winter months before spreading it on the fields during the growing season. This system has obtained the RAV certificate in 2021 with a quantified reduction of 8.4 kg NH_3 emission per cow per year. For 2030 we assumed that separation of urine and faeces will be used for 25% of the cows and by 2040 for 50%, which results in a reduction of 4.1 kton NH_3-N emission per year in 2030 (8.4 kg NH_3 * 2.3 million cows * 25% * 14/17 = 4.15) and about 10 kton NH_3-N emissions in 2040 as stable systems with higher reductions will be available. In the future likely new stables will be developed with even larger emission reductions, e.g. the Lely sphere[17], which might increase the potential emission reduction and the saved N can replace mineral fertilizer.

3.3.3 Acidification of manure storages

Slurry acidification is another solution to reduce ammonia emissions, by strongly increasing the NH_4^+: NH_3 ratio (Hjorth et al., 2015). Reduction of pH of slurry inhibits the activity of bacteria responsible for the nitrification of NH_4^+ (pH that maximizes the nitrification is 7.5-8) and keeps N longer available for crops and less susceptible to leaching (Fangueiro et al., 2015). In addition, the lower pH will also reduce the methanogenesis and decrease methane emissions from the manure storage. The most common additive for acidification is sulphuric acid, which reduces the pH of manure to 3.8-5.5 (Pedersen et al., 2017).

According to Bussink et al. (2011) the potential reduction of NH_3 emission due to acidification in stables is 35%, during storage 90% and during application 85%. This results in total to a 60% reduction of NH_3 emissions for cattle, which leads to increase in effective N of 32 kg N/cow. They assume a potential reduction in N fertilizer requirement of 15-30 kg N/cow. If we assume 20 kg N fertilizer less per dairy cow, this could reduce the fertilizer input by 32 kton N based on 1.6 million dairy cows. If we extrapolate this to pigs on the basis of the manure volumes (about 25% of the cattle manure), the savings would increase by 8 kton, resulting in a potential reduction of 40 kton. We assume that 15% of all cattle and pig liquid manure will be acidified by 2030 and 50% by 2040.

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[16] https://www.pig333.com/articles/the-trac-system-an-option-for-reducing-ammonia-emissions_17880/

[17] https://www.lely.com/nl/sphere/

The use of sulphuric acid may lead to problems regarding the safety of the handler and an excess of sulphur in slurry might lead to water quality problems on the long term. Therefore, some other acids are being considered as well, such as organic acids. Fuchs et al. (2021) have described that acetic acid even gives a better result probably because of the antimicrobial activity of acetic acid. Since these acids can be converted to methane, the cost of their use can be compensated by the yield of methane. This methane not only comes from the caloric content of the organic acid, but since the acidification will stop the methane production in the manure storage, once this manure is used in a biogas fermenter, there will be a much higher production of biogas. A recent Interreg project, Baltic Slurry Acidification (2019), has shown this same effect using sulphuric acid. A few developments have shown that the same acidification can be obtained by using various sources of sugar, which after adding to the manure cellar is converted to organic acids reducing the pH from 8 to below pH 6 and in so doing reducing the NH_3 losses from the manure. The advantage of using sugars is that farmers do not like to work with the strong sulphuric acid and furthermore sulphur is abundantly available in Dutch agriculture[18]. There is no need to add more sulphur to the system.

3.3.4 Cover crops

Cover crops are grown after harvest of the main crop to prevent bare fields, with the main purpose of retaining nutrients, thereby reducing the need for additional nutrient inputs over the following season, as well as preventing N leaching losses. The use of cover crops also can have additional benefits, such as an increase in nutrient retention for the following growing season, an increase in soil fertility over time, the potential for carbon sequestration in agricultural soils and an enhancement of biodiversity. As a result, cover crops have been included as an option in one of the three greening measures of the EU’s Common Agricultural Policy. Since 2019 it is obligatory to grow cover crops in the Netherlands after the harvest of maize that is grown on sandy soils. This is to prevent N leaching. The leaves and the roots of these cover crops are normally ploughed in the soil.

Many studies have investigated the potential of cover crops to reduce NO_3 leaching. Usually, a distinction is made between non-legume and legume cover crops. Non-legume cover crops are generally effective at reducing NO_3 leaching, with several studies reporting average reductions around 50% (Quemada et al. 2013; Thapa et al. 2018; Valkama et al. 2019). Legumes on the other hand have a lower potential to reduce leaching losses, but are able to introduce extra N into the system through fixation and are therefore more suitable as a green manure.

Lesschen et al. (2021) made an assessment of the potential of cover crops for soil C sequestration in the Netherlands. In 2017 cover crops were grown at 267 kha, of which a large part is on sandy soils after maize, as this is an obligation from the Nitrates Directive. They estimated that cover crops could be grown on an additional 150 kha. On average 2 ton carbon from the cover crops would be added to the soil (Selin Norén et al., 2021). Assuming an average CN ratio of 25, about 80 kg N is being sequestered in the plant material as well. Otherwise a large part (about 75%) would have been leached. This means that with an additional 150 kha of cover crops N leaching could be reduced by 9 kton N per year and the same amount of fertilizer could be saved in the following crop season.

An alternative would be to harvest the cover crop and fractionate it in a biorefinery, see Section 3.2.1. Not only non-leguminous plants like fodder radish, Japanese oats or yellow mustard can be applied but also legumes like red clover, fodder vetch and lupine can be used benefitting of their ability to fixate N from the air. Harvesting these cover crops removes the excess of N on sandy soils from those fields in order that the next season can start with as little excess N leaving more room for the application of digestate in spring. However, as these cover crops are mainly grown during autumn the harvest will be difficult and often the yields are too low. In addition many farmers grow the cover crops for soil fertility and carbon sequestration reasons, therefore we don’t expect that large quantities will be harvested for biorefinery yet.

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[18] https://www.mestverwaarding.nl/kenniscentrum/3188/discussiepaper-ncm-platform-groen-gas-nmi-en-sanovations-over-biologisch-aanzuren-van-mest

3.3.5 Nitrification inhibitors

Nitrification inhibitors are substances, which reduce the conversion of ammonium to nitrate and reduce in that way the emission of N_2O, a strong greenhouse gas, but this also limits nitrate leaching. Several commercial nitrification inhibitors are available such as DCD (dicyandiamide) and DMPP (ENTEC), which are often incorporated in mineral fertilizers. However, they can also be added to manure or even used on grassland to reduce emissions from urine patches.

A meta-analysis by Gilsanz et al. (2016) showed that these nitrification inhibitors can reduce N_2O emission by 30-50%. Kuikman et al. (2010) made an estimate for the Netherlands that the realistic reduction in N_2O emissions as result of nitrification inhibitors is about 1.0 kton N per year (0.3 kton for mineral fertilizer and 0.7 kton for manure application). Although N_2O is a very strong greenhouse gas, its contribution to N losses is only small. However, nitrification inhibitors also reduce leaching of nitrate, which is a much bigger loss of N. According to a meta-analysis inorganic N leaching can be reduced on average by 48% using nitrification inhibitors (Qiao et al., 2015). However, there is also a risk on increased ammonia emissions. The net reduction in N losses to the environment was on average 16.5% (Qiao et al., 2015).

Total N leaching in the Netherlands is estimated at between 45 and 75 kton N per year based on the LWKM and NEMA models. However, this is based on the N surplus, and cannot be directly allocated to the different N inputs. If we assume that 40% of the N leaching is related to mineral fertilizers (about 65% of the N fertilizer is used in the dairy sector, based on Agrimatie, but N leaching is lower under grassland), the use of nitrification inhibitors for all ammonium based fertilizers could reduce N leaching by 9.2 kton N. If nitrification inhibitors are also used for manure, the reductions can be even higher with an additional 13.8 kton N[19]. For 2030 we assume the full potential is used for mineral fertilizer and 25% for manure, and for 2040 75% of the potential.

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[19] 60 kton N leaching assumed, 60% share of manure and 40% mineral fertilizer, 80% use and 48% reduction in N leaching.

4 Results and discussion

4.1 N flows in Dutch agriculture

For the quantification of the N flows in Dutch agriculture we used results from the NEMA model and complemented these with data from databases such as CBS and FAOSTAT (Table 1). The results, as shown in Figure 6, are based on 2020 data. Fertiliser and feed import are the major inputs of N to the agricultural system. The amount of N in livestock products is about four times larger than crops produced for food and industrial purposes. The net export of food products in terms of N is about the same as what is consumed within the Netherlands. Most of this export consist of livestock products. Besides food products also a lot of N in manure is exported. Ammonia (NH_3) and dinitrogen (N_2) emissions and N leaching and runoff are the major losses from the agricultural system. Although N_2 is not a reactive N emission, it still contributes to lower N efficiency, as the N is not fixed in food products.

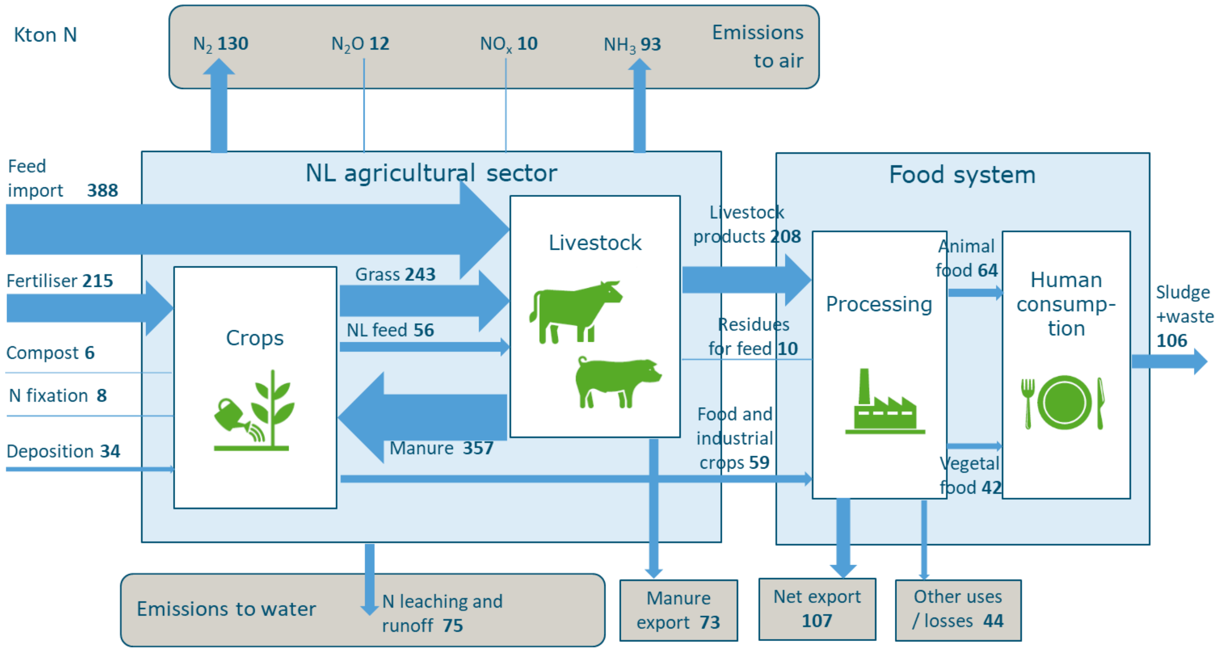

Figure 6 *N flows (in kton N) in the Dutch agriculture and food system for the year 2020. Source data are explained in Table 1.*

Table 1 *Source data and explanation for each of the N flows from Figure 6 for the year 2020.*

Flow	**Value (kton N)**	**Source and explanation**
External N input		
Mineral fertilizer	215	CBS data (mineral balance agriculture, average 2019-2021)
N fixation	8	CBS data (mineral balance agriculture)
Deposition	34	CBS data (mineral balance agriculture)
Compost	6	NEMA
Imported feed	388	Net import of feed based on FAO food balance and trade data (including soybean and rapeseed cakes and unprocessed oil crops)
N emissions		
N leaching and runoff	75	NEMA
N_2	130	Calculated remaining N flow from agricultural sector
N_2O	12	NEMA
NO_x	10	NEMA
NH_3	93	NEMA
Internal N flows		
Manure input	357	CBS data (mineral balance agriculture)
Grass	243	CBS data (mineral balance agriculture)
Feed from NL	56	CBS data (mineral balance agriculture) and FAO food balance data
Processing and consumption		
Food crops	59	CBS data (mineral balance agriculture)
Livestock products	208	CBS data (mineral balance agriculture)
Processed feed	10	Calculated remaining N flow from total feed intake
Consumption animal food	64	FAO food balance data per capita multiplied by population
Consumption plant food	42	FAO food balance data per capita multiplied by population
Outputs		
Net food export	107	Derived from FAO food balance data (88 kton animal products and 19 kton plant based products)
Other uses and losses	44	Calculated remaining N flow from food system
Manure export	73	CBS data (mineral balance agriculture)
Sludge and waste	106	Sum of animal and plant food (no net fixation)

4.2 Potential for NUE improvement options

4.2.1 N savings

For each of the improvement options the N savings have been estimated for the year 2030 and 2040 according to the descriptions of Chapter 3 (Table 2). The N savings are either a reduction in N fertilizer use, a reduction in N feed import or a reduction in N emissions, which can reduce the need for mineral fertilizer. As some of the options also affect the impact of other options, we also made a correction to account for potential double counting. For example, the striping of ammonium during anaerobic digestion will be less effective if other measures that reduce ammonia emissions, such as filters on stables and acidification, are also implemented.

Table 2 *N savings of the improvement options for 2030 and 2040 for the effect of the individual options and with corrections to account for double counting (values underlined).*

Improvement options	**2030**	**2040**	**2030 corrected**	**2040 corrected**
Reduce mineral N fertilizer use				
Alternative use of poultry manure	0.0	8.0	0.0	8.0
Mineral concentrates	7.0	10.0	7.0	10.0
Stripping of ammonia during anaerobic digestion	5.5	27.6	5.5	20.7
Recycling of human waste as fertilizers	3.1	9.5	3.1	9.5
Precision fertilisation	10.0	14.0	7.5	8.3
Grass clover	20.5	36.8	19.0	34.3
N fixing protein crops	4.5	4.5	4.5	4.5
Reduce import of feed				
Biorefinery				
Grass refinery	3.9	24.7	3.9	24.7
Crop residues (mainly sugar beet leaves)	0.8	3.9	0.8	3.9
Seaweed	0.0	3.5	0.0	3.5
Aquatic biomass (duckweed and azolla)	0.9	1.7	0.9	1.7
High productive grass species	1.4	2.7	0.7	2.7
Insects for animal feed	2.7	9.1	2.7	9.1
Synthetic amino acids in feed	2.5	5.0	2.5	5.0
Increase resistance of proteins in cows diets	4.8	12.0	4.6	9.8
Reduce N emissions				
Reduce NH$_3$ emissions from stables and storages				
Chemical or biological filter on stables	4.4	4.4	4.4	4.4
Separated collection of urine and faeces in stables	4.1	10.0	4.1	10.0
Acidification of manure storages	6.0	20.0	6.0	15.0
Reduce N emissions from agricultural fields				
Cover crops	9.0	9.0	7.9	7.2
Nitrification inhibitors	13.1	20.4	11.5	16.3
Total	**104**	**237**	**97**	**209**

Figure 7 provides a summary of the N savings for the main categories of improvement options. For 2030 the total N savings are estimated at 97 kton, of which most can be obtained by measures the reduce the mineral N fertilizer use, of which the use of clover in grassland is the main option. By 2040 the total N savings are estimated at 209 kton. Reduced fertilizer use and mineral fertilizer substitutes are the main options for N savings, but by 2040 also more feed related options become important, of which grass refinery contributes most.

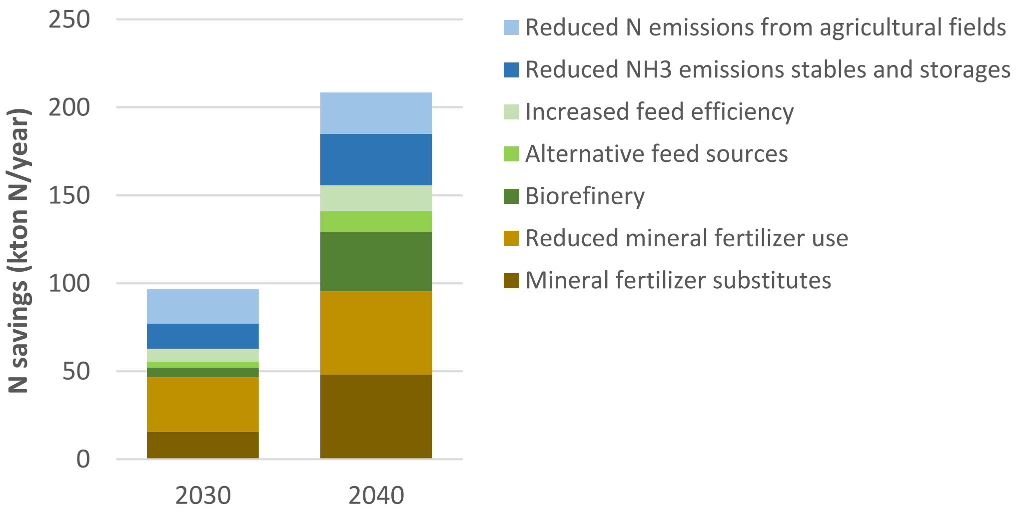

Figure 7 *N savings (kton N) for NUE improvement options in Dutch agriculture, aggregated to main reduction categories.*

4.2.2 Nitrogen use efficiency

Table 3 shows the N flows for the 2030 and 2040 scenarios to account for the effect of the above described improvement options. The amount of mineral fertilizer can be reduced by 57% in 2040 and the import of feed by 16%. NH_3 emissions can be reduced by 18% in for the 2030 scenario and 38% by 2040, this last reduction is already close to the reduction target in the national programme rural areas (NPLG) of 39 kton NH_3. N_2 emissions can be reduced by 43%, although this has no direct benefits for the environment, it does improve the NUE of the food system.

Table 3 *N flows (kton N) in the Dutch agriculture and food systems for 2020 and the scenarios for 2030 and 2040 with the improvement options (based on the results corrected for potential double counting).*

Flow	**2020**	**2030**	**2040**
External N input			
Mineral fertilizer	215	151	93
N fixation	8	32	47
Deposition	34	30	25
Compost	6	6	6
Imported feed	388	372	328
N emissions			
N leaching and runoff	75	55	48
N_2	130	117	74
N_2O	12	11	10
NO_x	10	9	9
NH_3	93	76	58
Internal N flows			
Manure input	357	373	405
Grass	243	243	243
Feed from NL	56	56	56
Processing and consumption			
Food crops	59	59	59
Livestock products	208	208	208
Processed feed	10	10	10
Consumption animal food	64	64	64
Consumption plant food	42	42	42
Outputs			
Net food export	107	107	107
Other uses and losses	44	44	44
Manure export	73	64	41
Sludge and waste	106	106	106

Based on these N flows, the NUE of the Dutch agricultural system has been calculated. The resulting NUE values are shown in Table 4 for the year 2020 and the scenarios for 2030 and 2040. In addition, the soil N surplus (soil N inputs minus N uptake) and the external N input (mineral fertilizer + feed import) are provided. For crop production the NUE can increase from 58% in 2020 to 62% in the 2040 scenario. For livestock the increase in NUE is smaller, from 30% in 2020 to 33% in 2040, as most of the improvement options replace imported feed, but do not reduce the total feed intake. The NUE for Dutch agriculture can increase from 40% in 2020 to 52% in the 2040 scenario. In the 2040 scenario the N soil surplus is reduced by 17% and the external N input is reduced by 182 kton N (-30%).

Table 4 *The NUE, soil N surplus and external N input indicators of Dutch agriculture for 2020 and the scenarios for 2030 and 2040 with the improvement options.*

Indicator	2020	2030	2040
NUE crop production	58%	61%	62%
NUE livestock production	30%	31%	33%
NUE agriculture	40%	44%	52%
Soil N surplus (kton N)	262	233	219
External N input (kton N)	603	533	421

A recent paper of Leip et al. (2022) quantified N flows and NUE for the EU for the year 2015. Based on this paper the NUE for crop production was 63%, for livestock production 19% and for agriculture as a total 40%. This shows that in the Netherlands the NUE of livestock production is relatively high with 30%, while crop production has a lower NUE due to the high manure and fertilizer inputs. With the improvement options the NUE can be improved and also become higher than the EU average for crop production and agriculture. In the NUE calculation we did not account for the N in exported manure. One could consider the exported manure as product as well, since it might be used for food production abroad. This would increase the NUE of the agricultural system. However, we did neither account for the N losses related to the production of imported feed, which would lower the NUE (Quemeda et al., 2020).

4.2.3 Indirect impacts of improvement options

Besides an improvement of the NUE, the improvement options can also have other positive impacts. Although a full environmental impact assessment was beyond the scope of this project, we can discuss some of the benefits. The main impact is on land use outside the Netherlands. For all options that reduce the import of protein rich feed, less land is required to grow these feed crops. Especially a reduction in the import of soy can have positive impacts on land use, as currently there is still a trend of increasing cropland expansion in South America, which directly or indirectly results in deforestation and loss of biodiversity. For example, for the option of grass biorefinery, if the 24.7 kton N that could be used for pig and poultry feed in 2040 would replace the soybean import, this would reduce the demand for soybean land in South America by about 125 kha.

For the improvement options ‘alternative use of poultry manure’ and ‘recycling of human waste as fertilizer’ there is an additional N saving, as currently these N sources are partly incinerated. To prevent NOx emissions, these installations have deNOx filters, for which NH_3 is used, which will convert NO_x to N_2. Without incineration, also the additional NH_3 is not required, which might give a N savings of 12 kton N in the 2040 scenario.

4.3 Discussion

To stay within the planetary boundary limits for N use, this report shows a variety of options that all together can reduce the N input and N losses by more than 200 kton in 2040. This can increase the NUE in the Netherlands from 40% to 52% in 20 years. Not all options will be fully applied because of either economic reasons or societal reasons that people are adverse of technical solutions or of the expected nuisance or the time it might take for getting permits to install a new technology. Certainly, technologies with good economic potential will at last be implemented. Technologies that nowadays look marginal can also become more attractive because of market developments or by technical improvements, but also due to government regulations, e.g. emission allowances or mandatory implementations. In most cases the numbers mentioned in this report are the best estimations we could make on the basis of existing literature or practical information we gathered. However, future projections always remain uncertain and results should therefore be used carefully. As the current policy around N is strongly in development, the assumptions underlying the implementation of the improvement options can change. For example, the recently announced abolishment of the derogation for the maximum manure application is not yet included in the results of this study as effects on changes in manure market and areas of grassland are not yet clear.

For ammonia a reduction of 18% in the 2030 scenario and 38% for the 2040 scenario should be possible with the selected improvement options. However, to reach the national targets for N emissions in 2030, the package of improvement options is not yet sufficient. Therefore a combination of a reduction in livestock numbers and technical and management options is needed to achieve these targets. This is in line with other studies in which integrated assessments for Dutch agriculture were made (de Vries et al., 2022; Gies et al., 2023).

N use can also decrease because of changes in diet. Reducing the consumption of animal products and at the same time increasing the consumption of plant-based proteins will lower N usage especially when leguminous plants are used as the resources. However, under the Dutch climate conditions, grass still will be the crop with the highest protein production per ha, and therefore the Netherlands still is a suitable place for dairy production. Improving the N use efficiency of agriculture in the Netherlands in combination with a lower consumption of animal products would be the best solution on a global scale. If the planetary boundary for N is as stringent as calculated by Steffen et al. (2015) all mentioned options can contribute all over the world to a sustainable food supply.

Improving the NUE can also have synergies with reducing greenhouse gas emissions. First of all because of lower N_2O emissions, but also because of additional carbon sequestration by plant roots or above the ground by growing cover crops. There certainly are synergies in reducing methane emissions and N emissions in manure management systems, e.g. by lowering the pH of the slurry or separate collection of urine and faeces. Climate change mitigation policies might therefore also provide incentives to improve the NUE in agriculture.

5 Conclusions

In this study we quantified the N flows and nitrogen use efficiency of Dutch agriculture and presented a range of options to improve the efficiency and reduce N emissions. The current NUE of Dutch agriculture is 40%, which means that 60% of the N input required to produce the crop and livestock products is lost. With the options assessed the NUE can be improved to 52% in the 2040 scenario. Maintaining the same level of agricultural production is possible with a reduction of 57% of the mineral N fertilizer use and a 16% reduction in N feed import. In addition N emissions to the environment can be reduced. Although N inputs have already been reduced since 1990, this analysis shows that a further reduction is still possible, while maintaining the current level of livestock and crop production. Combining these (technical) improvement options with changes in the human diet, with lower share of livestock products, could increase the NUE even further, as the NUE of livestock production is much lower compared to crop production.

For the short term (2030) the options that reduce N emissions and replace mineral fertilizer are most promising, e.g. mineral concentrates, use of grass clover, precision fertilisation and cover crops. These options have been investigated well, and can be implemented without major changes in the production systems. Most of the options to replace imported feed proteins with local sources, e.g. through biorefinery, will require more time for large scale application. For the uptake of these options a holistic approach is needed, which requires collaboration and multi-disciplinary research programmes to reduce cost and conflicting regulatory issues.

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Report 3258
ISSN 1566-7197

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