Exploring the effects of a larger share of organic agriculture on production and sustainability

A case study of Drenthe

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Contact office.pps@wur.nl for access to data, models and scripts used for the analysis.

Abstract

European agriculture causes 10-12% of EU greenhouse gas (GHG) emissions and contributes substantially to nitrogen (N) pollution, thereby causing damage to human health, ecosystems and climate and imposing considerable societal costs. With the Farm to Fork (F2F) strategy, the European Commission aims to tackle these problems while retaining high food productivity. One of the aims of the F2F strategy is to move to a system in which 25% of the agricultural land is farmed organically. Organic agriculture is often seen as a more sustainable way of farming, for instance enhancing nutrient circularity and reducing GHG emissions and nutrient losses. On the other hand, it is argued that the lower yield of organic agriculture compared to conventional agriculture outweighs its benefits. The current study analysed the effects of increasing the share of organic agriculture to 25% of the total agricultural land in the province of Drenthe, the Netherlands. The Co-Product Management and Analysis (CoPMA) model was used to analyse various scenarios with 25% of the land under organic agriculture and comparing them to the current situation in terms of regional food and feed productivity, N cycling and GHG emissions. Regional productivity would be substantially lower in scenarios with 25% of the land under organic agriculture. Results showed to a system with 25% of the land under organic agriculture could improve N cycling, but it could also cause a decrease in N efficiency (i.e. O/I ratio). It was also shown that less GHGs could be emitted, both when expressed per land area and per kg N in useful output. Only when converting large shares of arable land to organic, GHG emissions per kg N in useful output was higher than in the current situation. A farming system in Drenthe with 25% of the land under organic agriculture could potentially produce enough feed to meet the regional feed requirements, but there would be a substantial shortage of manure to meet the nutritional requirements of organically grown crops. Organic dairy farming could contribute to the reduction of GHG emissions per unit of food produced, but organic arable farming has the opposite effect. In moving towards a system with 25% of the agricultural land under organic agriculture, it should be considered to focus on organic dairy farming, rather than on organic arable farming.

List of Abbreviations

25OA	25% OA scenario
25OA_E	25% OA scenario equally distributed
25OA-FE	25% OA scenario without feed export
25OA-MI	25% OA scenario without manure import
BNF	Biological nitrogen fixation
CA	Conventional agriculture
CH_4	Methane
CO_2	Carbon dioxide
CoPMA	Co-Product Management and Analysis
CyCt	Nitrogen cycling count
EU	European Union
F2F	Farm-to-Fork
GHG	Greenhouse gas
GWP-100	Global warming potential
N	Nitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NO_3^-	Nitrate
O/I ratio	Nitrogen output/input ratio
OA	Organic agriculture
OA:CA ratio	Organic:conventional yield ratio
Ref	Reference scenario
t	Metric tonne
TAN	Total ammoniacal nitrogen

Contents

1 Introduction

1.1 Background

Agriculture accounts for approximately 10-12% of total greenhouse gas (GHG) emissions in the European Union (Dace & Blumberga, 2016; EEA, 2022). In addition, nitrogen (N) losses from crop production and animal husbandry cause air pollution (e.g. fine-particulate matter), groundwater pollution (e.g. due to nitrate leaching), surface water pollution (e.g. eutrophication) and related biodiversity loss (Erisman et al., 2013; Galloway et al., 2008; Pozzer et al., 2017). In the past decades, N pollution has gained increasing attention in the EU and consequently reduced. For instance, NH_3 emissions and N surplus have decreased 20% between 1900 and 2004 (van Grinsven et al., 2013). Despite these reductions, the societal costs of agricultural N pollution, such as damage to human health, ecosystems and the climate, are estimated at €35–230 billion/year. These costs are substantially higher than benefits of N in agricultural production, which are estimated at €20–80 billion/year (van Grinsven et al., 2013).

The European Commission proposed several measures in the Farm-to-Fork (F2F) strategy to combat the issues related to agricultural GHG emissions and N pollution among others (EC, 2020). With the F2F strategy, the European Commission aims for a more circular agricultural system, reducing GHG emissions and N losses by 50%, and artificial fertiliser use by 20% in 2030, while maintaining a high productivity. In addition, it aims for at least 25% of the agricultural land in the EU to be farmed organically (EC, 2020). Although positive steps are being taken towards these goals (EC, 2021), it is often debated whether the F2F strategy is sufficient to meet its own goals (Billen et al., 2024). In addition, recent events and protests have caused the goals to be watered down, for instance scrapping the 50% pesticide reduction goal (Armstrong, 2024).

Organic agriculture (OA) is often proposed as a sustainable alternative to conventional agriculture (CA) (Foley et al., 2011; Muller et al., 2017), although this is heavily contested (Leifeld, 2012). OA should be able to partially close local nutrient cycles and reduce nitrogen pollution (Foissy et al., 2013), but due to specialisation of organic farms and strict EU regulations, this is generally not achieved (Hofstad & Schröder, 2002; Løes & Adler, 2019). The specialisation barrier can partly be overcome by close collaboration between organic arable and livestock farms in the same region through the exchange of manure and feed (Billen et al., 2021; Foissy et al., 2013). However, in case of successful collaboration, there would still be a substantial shortage of N from organically produced manure to achieve high crop yields in many European countries, including the Netherlands (Migchels et al., 2023; Reimer et al., 2023). Therefore, organic arable farms are currently partly dependent on manure from conventional livestock farms (Løes et al., 2017). For instance, in the Netherlands up to 30% of manure applied may be sourced from conventional farms (SKAL, n.d.). Besides, the N shortage is partially overcome with biological N fixation (BNF) by the inclusion of legumes and green manure in the rotation (Billen et al., 2021).

It is often suggested that OA has the potential to substantially reduce GHG emissions, mainly due to the exclusion of artificial fertilisers and pesticides (Balogh, 2023; Holka et al., 2022). GHGs emitted from agricultural practices are mainly CO_2, CH_4 and N_2O. According to Balogh (2023), the increase in land share under OA in the EU between 2000 and 2020 (i.e. from 2.19% to 9.16%) has caused substantial reductions in total agricultural GHG emissions. On the other hand, a farm-level modelling study by Bos et al. (2014) showed that, despite the elimination of synthetic fertilisers and pesticides, GHG emissions from organic crop and vegetable production per unit of product are 15-40% higher than from their conventional counterparts. This difference is mainly caused by substantially higher diesel use and lower crop productivity in organic compared to conventional cropping (Bos et al., 2014). In organic livestock farming, GHG emissions may be significantly lower compared to conventional systems due to less reliance on concentrates and omission of mineral fertilisers (Bos et al., 2014; Frank et al., 2019; Gross et al., 2022). For instance, GHG emissions per kg of milk were shown to be 5-12% lower for organic dairy farms compared to conventional (Bos et al., 2014; Frank et al., 2019).

Maintaining a high productivity is often seen as an issue in OA. Lower yields in OA are mainly due to the exclusion of mineral fertilisers and use of chemical crop protection agents like pesticides and herbicides. The resulting issues with soil fertility and pest, disease and

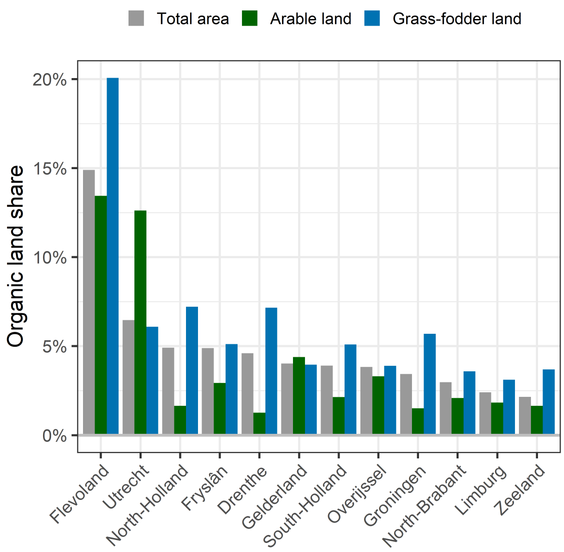

Figure 1.1: The proportions of agricultural land under OA in 2022 in the Dutch provinces. The bars indicate the land share of total agricultural land (Total), arable cropland (Arable) and grass- and fodder cropland (Grass-fodder land). Land in conversion to OA was considered as organic land. (Source: CBS, 2023).

weed management are partly tackled by implementing more diverse crop rotations that include legumes (Wijnands, 1999). Indeed, Connor (2022) showed in a review that the incorporation of green manure and legumes in organic rotations partly mitigate lower yields related to N shortage at field level, with experiments showing organic:conventional (OA:CA) yield ratios of 0.75 to 0.91, depending on the crop. However, as including leguminous crops and green manures in the rotation requires land, productivity at the farm or regional level is more severely affected. Connor (2022) showed that the OA:CA yield ratio at the regional level is estimated to be 0.43 to 0.74. It is therefore often questioned whether organic agriculture can feed the world with its current diet within the planetary boundaries for land-use (Connor, 2008). In contrast, the OA:CA yield ratio for livestock production is generally higher than that for crop production. Gaudaré et al. (2021) estimated the yield ratio for dairy cattle at 0.86 and for meat pigs and poultry at 0.91.

The feasibility of conversion to OA is often questioned (Muller et al., 2017). For instance, farmers in the Netherlands perceive profitability, financial risks and lacking demand for organic products as strong constraints to converting to OA (Verburg et al., 2022). The Netherlands is lagging behind other EU member states in terms of the land share under OA. In fact, the land share under OA in the Netherlands in 2020 was 3.7% compared to average of 9.1% in the EU (CBS, 2023; EC, 2023). Further zooming in to the provincial scale in the Netherlands reveals some remarkable differences in adoption rates. For instance, the total OA land share in 2022 is relatively high in Flevoland (14%; Figure 1.1) and relatively low in the provinces of Limburg and Zeeland (2.4 and 2.1%, respectively; Figure 1.1) (CBS, 2023). In general, the OA adoption by farmers cultivating grass- and fodder crops is higher than by farmers with arable land. This observation holds true for most provinces, although the differences between arable and grass- and fodder cropland are more pronounced in some provinces, such as Drenthe (Figure 1.1) (CBS, 2023).

It is unclear how the agricultural system needs to be shaped to facilitate a self-sufficient organic land share of 25% (i.e. without using conventional inputs), as was formulated in the F2F strategy. The current thesis will use a case study of farming system of the province of Drenthe to assess the effect of increasing the land share of OA to 25% on sustainability indicators – GHG emissions, nutrient cycling, productivity – using a modelling approach. The term 'farming system' can be interpreted in many ways (Giller, 2013), but in the current study, it refers the agricultural land and practices in the entire region in the province of Drenthe. In addition, the study addresses the issue of regional self-sufficiency of OA in Drenthe, in terms of N for crops and animals.

1.2 Research questions

The main research question addressed in this project was formulated as: *How will a farming system with 25% of land under organic farming perform on regional N cycling, GHG emissions and crop and livestock production in the province of Drenthe?*

To answer this main question, the following sub questions were answered:

1. How does the agricultural system in Drenthe currently perform in terms of N cycling, GHG emissions and crop and livestock production?
2. How will the agricultural system in Drenthe perform in terms of N cycling, GHG emissions and crop and livestock production with 25% of the land under OA?
3. How can the land shares under OA be distributed between grass-fodder and arable land to ensure manure or feed self-sufficiency under 25% organic agriculture?

2 Methods

2.1 Study region

The province of Drenthe has a total land area of 268,270 ha, of which 147,353 ha is under agricultural land-use. The south-west of Drenthe is characterised by a large share of dairy farms with grassland on sandy soils. In the north-east, arable farms dominate the agricultural land with starch and ware potato, sugar beet, barley and onion as the main crops. The soil in this region consists of a sandy soil with a top layer that is high in organic matter due to the historical presence of peatland. In between these regions, a mix of arable and dairy farms exists with some mixed farms dispersed over the region. Arable and dairy farming account for the major part of agricultural land use, with a combined area of 144,029 ha of land. Poultry and pig farms with little land are distributed throughout the entire province (Vonk et al., unpublished). The total and organic cropping areas and numbers of cattle, pigs and poultry are shown in Table 2.1. The areas for horticultural, fruit and flower production and the number of sheep and goats are small (CBS, 2023). These are therefore excluded from the current study.

The share of land under OA in Drenthe was 4.6% in 2022 (CBS, 2023). The share of organic arable land is only 1.3%, while that of organic grass- and fodder cropland is 7.2%. Of the total organic arable cropland, approximately 74% was dedicated to cereals (e.g. rye, barley, triticale) and 8% to various vegetables (e.g. onions) and legumes (e.g. green beans, peas). On the rest of the organic arable cropland a wide variety of crops is grown on small areas. Organic livestock accounts for 3.6%, 1.2% and 1.9% of the total number of cattle, pigs and poultry, respectively. An average organic or conventional arable farm in Drenthe has approximately 55 ha of land. An average organic dairy farm has approximately 53 ha of pasture, whereas a conventional dairy farm has only 30 ha. The number of cows per farm is higher on conventional farms than on organic farms (i.e. 121 versus 103 adult dairy cows, respectively). The number of animals on pig or poultry farms is approximately five times lower on organic farms (CBS, 2023).

2.2 Model description

The model used in the current study was an adapted version of the Co-Product Management Analysis (CoPMA) model developed by Vonk et al. (unpublished). The CoPMA model was developed to calculate various sustainability indicators at the farm and regional level: food and feed production, N cycling indicators, GHG emissions, energy balance and soil organic matter changes. The model includes a crop component and a livestock component (Figure 2.1). In the land-based component, three compartments were distinguished, being the soil, food crops (i.e. arable crops) and feed crops (i.e. grass-clover pasture and silage maize). In the non-land-based component, an animal compartment and manure compartment were distinguished.

The system boundary is considered the total agricultural area in the province of Drenthe. All flows except CO_2 and CH_4 are quantified in terms of nitrogen, following a material flow analysis approach. CO_2, CH_4 and N_2O emissions are quantified in terms of CO_2-equivalents. Manure, food and feed are considered outputs if they leave the agricultural land of Drenthe. Thus, manure and feed that are utilised on other farms in the region than where they are produced, are considered internal flows. Resources imported from outside the region (e.g. fertilisers, pesticides, feed from external sources) are considered inputs. GHG-emissions related to the production of these resources are included as well.

For my study, the model was adapted to account for differences between conventional and organic farming systems. Manure and feed distribution were adjusted in such a way that conventional and organic manure could only be applied on conventional and organic farms, respectively. In addition, biological N fixation (BNF) by green manure and pesticide use were integrated into the model. The model was only used to calculate food and feed production, N cycling indicators and GHG emissions at the regional level.

2.2.1 Crop component

Nitrogen fertilisation

Crops and pasture can be fertilised with green manure, animal manure or synthetic N fertiliser (Figure 2.1). The part of the N fixed in biological N fixation (BNF) by

Table 2.1: The area of different land-use types and the number of animals of different livestock in Drenthe in 2022 (CBS, 2023).

	Area (ha)			*Animal heads (#)*	
Type of land	Total	Organic	**Animals**	Total	Organic
Arable crops	60,641	748	**Cattle**	223,329	8,130
Grassland	67,068	5,691	**Pigs**	207,375	2,421
Fodder crops	16,320	277	**Poultry**	7,861,491	148,842

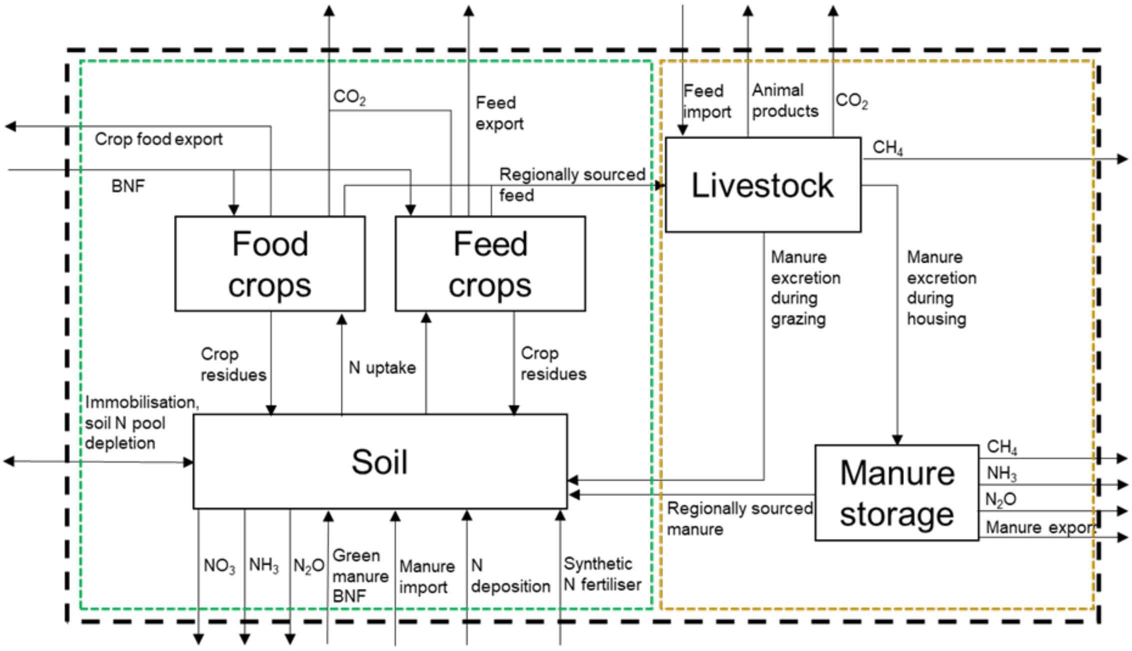

Figure 2.1: Schematic overview of the model system showing the inputs, outputs and internal flows (black arrows) on the regional level with different farm components in the region. Black dashed line indicate the system boundaries of the entire region (i.e. agricultural land of Drenthe), green dashed line indicates the crop component and orange dashed line indicates livestock component. Adapted from Vonk et al. (unpublished).

green manure that is available to the crop is based on an estimate by Couëdel et al. (2018) and is assumed to be taken up entirely by the subsequent crop (22 kg N ha^{-1}). Legumes, winter crops and all conventional crops were assumed to have no input from green manure.

Animal manure is either excreted during grazing (i.e. on grassland only) or sourced from dairy, pig and poultry manure storage in the region. For organic farms, it is also possible to import cattle slurry from outside of the region. Manure that is excreted during grazing is equally distributed over the grassland. The size of this flow is based on the time spent outside (CBS, 2019; Smolders & Plomp, 2012), the number of cows in the region and region-specific values for excreted N per cow (Appendix A) (CRF, 2019; Zom & Kasper, 2019). All other manure is assumed to move into manure storage and are based on the number of animals in the region and region-specific values for excreted N per animal (Appendix A) (CRF, 2019).

Regionally produced conventional and organic manure are equally distributed over conventional and organic land, respectively, or until the maximum amount of manure is reached. The maximum of regionally sourced manure application rate is determined by 1) the available amount of manure in the region, 2) the legal maximum N application from manure (170 kg N ha^{-1}) (RVO, n.d.), 3) the legal maximum phosphate application (70 and 95 kg P2O5 ha^{-1} for arable crops and pasture, respectively) (RVO, 2019) and 4) the effective N rate for maximum crop yield (see "Crop production").

N supply on conventional farms was supplemented with synthetic N fertiliser until the maximum crop yield was reached. N supply on organic farms was supplemented with imported cattle slurry until reaching

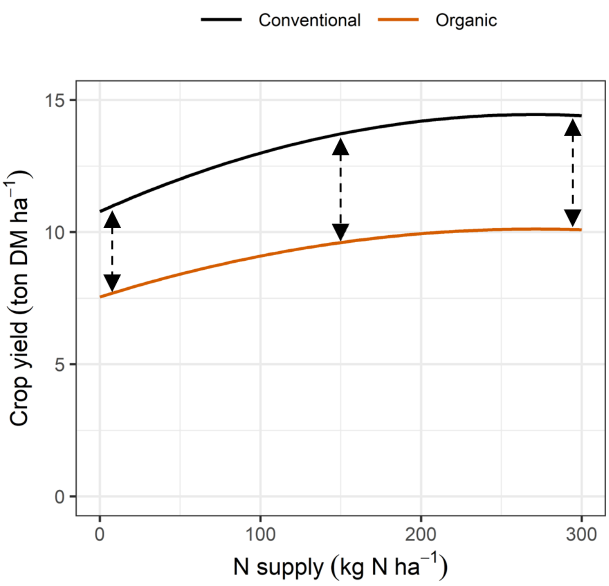

Figure 2.2: Yield response curves for conventional and organic starch potato. The dashed arrows indicate the yield difference between conventional and organic potato (OA:CA ratio of 0.7 (de Ponti et al., 2012)).

the legal maximum amount of N or phosphate, or the maximum crop yield.

Crop production

N uptake by crops was a combination of uptake from N fertilisation (i.e. effective N application), N from crop residues and soil N uptake (Figure 2.1). Effective N application rate was determined for each crop as the sum of 1) N in artificial fertiliser (i.e. considered 100% effective), 2) the amount of N from manure application that becomes available in the first year after application (van Dijk & van Geel, 2008; van Geel & van Dijk, 2013) and 3) the fixed N in crop residues of the preceding green manure in the rotation.

Crop yield was calculated as a function of the effective N application rate, based on crop-specific polynomial N response curves that were fitted using real-time data (Appendix C; starch potato: Rutgers and Malda (2012); spring barley: Timmer et al. (2021); sugar beet and silage maize: van Dijk et al. (2007); grass: Ten Berge et al. (2007); pea: Boskma (1964); green bean: Neuvel et al. (1994); onion: van den Brink et al. (2009); winter rye Dekker and van Dijk (2005)). Yield response curves for organic production were determined by multiplying the conventional response curve by the OA:CA yield ratios from de Ponti et al. (2012) (e.g. see Figure 2.2).

All crop residues are considered to be left on the field. The amount of belowground crop residues is based on fixed crop-specific ratios between harvested biomass and belowground biomass (Appendix C) (IPCC, 2019). Aboveground crop residues are based on a linear relationship with crop yield (Appendix C) (IPCC, 2019).

The entire yield of food crops (i.e. starch potato, sugar beet, green bean, onion) was exported as food. Grain crops (i.e. cereals and pea) were partly exported as food and partly utilised as feed for the livestock component. The fraction used as feed differs per scenario (see Section 2.3). Feed crops (i.e. grass-clover and maize) were used as feed for dairy cattle in the region and any surplus was exported as feed.

Nitrogen losses

N is lost from the system in the form of ammonia (NH_3), nitrous-oxide (N_2O) and nitrate (NO_3^-) (Figure 2.1). NH_3 is emitted from synthetic N fertiliser, manure and crop residues applied to the soil. NH_3 losses from synthetic N fertiliser are quantified as a fraction of the applied synthetic N (0.052 kg NH_3-N kg^{-1} N applied) (van Bruggen et al., 2023). NH_3 losses from manure application are quantified as a percentage of the total ammoniacal N (TAN; Appendix A) based on country-specific emission factors (EFs) (0.06 and 0.18 kg NH_3-N kg^{-1} TAN for crops and pasture, respectively) (van Bruggen et al., 2023). NH_3 losses from crop residues are quantified as a percentage of the total N in crop residues retained on the field, based on crop-specific EFs (Appendix C) (de Ruijter & Huijsmans, 2019).

N_2O emissions are the sum of direct and indirect N_2O emissions. Direct N_2O emissions are quantified as a percentage of artificial N fertiliser application (0.016 kg N_2O-N kg^{-1} N), manure application (0.006 kg N_2O-N kg^{-1} N) and crop residues (0.006 kg N_2O-N kg^{-1} N), based on EFs specific for wet climates (IPCC, 2019). Indirect N_2O emissions result from manure storage prior to import, NH_3 deposition and NO_3^- leaching originating from the farm. N_2O emissions from atmospheric NH_3 deposition are quantified as a percentage of the total NH_3 emitted, based on standard EFs (0.014 kg N_2O-N kg^{-1} NH_3-N emitted) (IPCC, 2019). N_2O emissions resulting from NO_3^- leaching are quantified as a percentage of the total NO_3^- leached, based on standard EFs (0.011 kg N_2O-N kg^{-1} NO_3^--N leached) (IPCC, 2019).

NO_3^- leaching is based on soil type-specific leaching factors for arable land as a fraction of the N surplus (i.e. difference between N inputs and outputs) after NH_3 and N_2O emissions. Results from the MITERRA-EUROPE model (Velthof et al., 2009) were used to calculate the leaching fractions, assuming a sandy soil, precipitation surplus of 300-325 mm, average annual temperature of 12°C, rooting depth of 40 cm and SOC content of 1-2%. NO_3^- leaching fractions for arable land and pasture are 0.75 and 0.27, respectively.

Other nitrogen flows

Other N flows include BNF by leguminous crops (i.e. green bean and pea), N deposition and N mobilization or mineralisation (i.e. soil N pool change) (Figure 2.1). N input from BNF by grass-clover is based on an estimated yearly N fixation rate in the Netherlands, assuming 15% clover on conventional pasture and 30% clover on organic pasture (Appendix C) (Hofstad & Schröder, 2002). BNF by other legumes is based on crop-specific N fixation rates (Appendix C) (Akter et al., 2018; Gollner et al., 2019). N deposition is a assumed to be 19.74 kg N ha^{-1} (Velders et al., 2018). The soil N pool change is determined by the difference between total N inputs and outputs, closing the soil N balance.

GHG emissions

Carbon-dioxide (CO_2; Figure 2.1) emissions are a result of direct emissions from the farm and indirect emissions from production of imported goods. Direct CO_2 emissions result from diesel combustion by agricultural vehicles during cultivation operations. Diesel consumption is based on crop-specific values from KWIN (2022) (Appendix C). Indirect CO_2 emissions result from the production of synthetic N fertiliser and crop protection agents. CO_2 emission factors per unit of energy used for diesel combustion (0.07 kg CO_2 MJ^{-1}) and N fertiliser production (7.81 kg CO_2 kg^{-1} N) are used to quantify indirect CO_2 emissions (Kränzlein, 2008). Due to a lack of crop-specific data, indirect CO_2 emissions related to the production of crop protection agents does not differ per crop (40 and 2 kg CO_2 ha^{-1} for conventional and organic crops, respectively) (Deike et al., 2008). The calculation of N_2O emissions is explained in the section "*Nitrogen losses*".

2.2.2 Livestock component

Feed input

Feed can be regionally produced (see "Crop production" in Section 2.2.1) or imported (Figure 2.1). Conventional and organic livestock can only be fed with conventional and organic feed, respectively. Dairy cattle are fed primarily with roughage (i.e. by grazing) and silage maize. Conventional dairy cattle are assumed to graze 18% of the time (1,552 hours yr^{-1}) and organic dairy cattle 38% of the time (3300 hours yr^{-1}) (CBS, 2019; Smolders & Plomp, 2012). Regionally produced concentrates (i.e. from grain crops) are equally distributed over the livestock in the region, limited by animal-specific feed requirements. Feed requirements are based on region specific averages of N intake (CRF, 2019; van Bruggen et al., 2023; Zom & Kasper, 2019). If feed produced in the region is insufficient to meet livestock feed requirements, feed is only imported in the form of concentrates.

Livestock production

Useful animal products are food products (i.e. milk, meat and eggs) (Figure 2.1). Production of organic farms is considered to be 12% lower for organic livestock (Gaudaré et al., 2021). Meat and egg production was quantified as the amount of N retained per year in these products based on region-specific values (Appendix A) (van Bruggen et al., 2023). The amount of milk produced was quantified in kg N retained in milk per cow each year (Appendix A) (Zom & Kasper, 2019).

The amount of manure excreted is based on the number of animals present in the region and region-specific values for excreted N for cattle, pigs and poultry (Appendix A) (van Bruggen et al., 2023; Zom & Kasper, 2019). In case the regional manure production was higher than the manure application on crops and pasture, the manure surplus was considered to be exported.

Nitrogen losses

N losses from the livestock component are in the form of NH_3 and N_2O emissions (Figure 2.1). NH_3 is emitted by conversion of ammoniacal N in urine and solid manure by bacteria. NH_3 emissions are quantified as a percentage of the TAN using standard EFs (Appendix A) (van Bruggen et al., 2023). N_2O is emitted from stored manure as a result of denitrification. N_2O emissions are quantified as a percentage of the N in excreted manure using standard EFs (Appendix B) (IPCC, 2019).

GHG emissions

CH_4 is emitted from enteric fermentation of the animals as well as from manure storage (Figure 2.1). CH_4 emissions from enteric fermentation for pigs and poultry are based on the number of animals and EFs per animal (Appendix A) (CRF, 2019). CH_4 emissions from dairy cattle is calculated based on the energy intake from feed (Appendix A) (CRF, 2019). CH_4 emissions from manure storage are the result of anaerobic decomposition of manure. These are quantified as the product of the number of animals and animal- and country-specific EFs (Appendix A) (CRF, 2019).

Indirect CO_2 emissions related to electricity use (i.e. ventilation, lighting, manure management systems and feeding installations) (Appendix A) (Kränzlein, 2008; Witzke & Gocht, 2022). A standard CO_2 emission factor per unit of energy is used to determine the amount of CO_2 emitted (0.05 kg CO_2 MJ^{-1}) (Kränzlein, 2008). In addition the indirect CO_2 emissions related to the production of imported feed is considered and is based on animal specific values (Appendix A) (GFLI, 2023; van Bruggen et al., 2023; Vellinga et al., 2009).

N_2O emissions are calculated as explained in the section "*Nitrogen losses*".

2.3 Scenario description

The available land for agriculture in the region was 144,029 ha and was the same across all scenarios. Apart from the reference scenario, all scenarios had an organic land-share of 25% of the total agricultural land. The ratios of land allocated to different crops within the different classes of farm systems (i.e. organic arable, organic dairy, conventional arable and conventional dairy) remained the same in all scenarios. Crops that were grown in the region included starch potato, spring barley, sugar beet, silage maize, grass-clover, onion, green beans, peas and winter rye (Table 2.2). The division of organic agricultural land between arable and dairy (i.e. pasture and feed crops) farms, the amount of animals present in the region and the fraction of grain yield that is used as feed may differ between these scenarios.

Reference (Ref)

The reference scenario represents the current situation in Drenthe. The acreages of the different crops are based on actual data from Drenthe in 2022 (CBS, 2023). Because only part of the crops grown in Drenthe were represented (i.e. by extension only part of the total agricultural land), the area per crop was slightly increased to reach a total area matching the actual cropping area in Drenthe (Table 2.2). Of the conventional spring barley, 60% was used as feed, whereas 82% of organic rye, 80% of organic spring barley and 10% of pea yield is assumed to be feed (Bos & de Wit, 2005).The number of dairy cows, young stock, pigs and poultry in the current scenario are also based on actual data from Drenthe in 2022 (Table 2.3) (CBS, 2023).

25% OA (25OA)

In the 25% OA scenario, the share of land under OA was increased from 4.6% to 25%. The ratio between the arable land share under OA and the grass-fodder land share under OA was the same as in reality. Since the current share of organic arable and grass-fodder area are 1.3% and 7.2%, the shares under OA of arable and grass-fodder land were 6.6% and 38.4%, respectively. The ratio between crops within each class (i.e. conventional arable, conventional grass-fodder, organic arable, organic grass-fodder) remains the same. The resulting area per crop is given in (Table 2.2). The number of dairy cows and young stock per hectare of pasture remains the same as in the reference scenario. The total number of pigs and poultry remains equal to the reference scenario (Table 2.3).

25% OA, No feed export (25OA-FE)

In the no feed export scenario, the area per crop remains the same as in the 25% OA scenario (Table 2.2). The number of organic cattle is increased so they consume all regionally produced organic silage maize and grass-clover (Table 2.3). The fraction of organic rye and spring barley that is used for feed is reduced to 61%, in order to match feed requirements of pigs and poultry with regional feed production. The number of pigs and poultry in the region remain the same as in the reference scenario (Table 2.3).

25% OA, No manure import (25OA-MI)

In the no manure import scenario, the area per crop is the same as in the 25% OA scenario (Table 2.2). The number of cattle is adjusted so they consume all regionally produced organic silage maize and grass-clover, similar to the no feed export scenario (Table 2.3). The number of organic pigs and poultry is increased (approx. 35-fold) to produce enough organic manure to reach the maximum manure application rate with only regionally produced manure (Table 2.3).

25% OA, Equal distribution (25OA_E)

In the 25% OA, Equal distribution scenario, organic arable land accounts for 25% of total arable land and organic grass-fodder land accounts for 25% of total grass-fodder land (Table 2.2). The number of organic cattle is adjusted in the same way as in the no feed export scenario (Table 2.3). The fraction of organic winter rye and spring barley that is used as feed is reduced to 16%. The number of pigs and poultry is equal to that of the reference condition (Table 2.3).

2.4 Model outcomes and analysis

For the different scenarios, regional food and feed production were quantified as the total amount of N in crop and animal products, divided by the total agricultural area (kg N ha^{-1}) (hereafter: productivity). In addition, relative changes in food productivity between the reference scenario and the scenarios with 25% of the area under OA were visualised. Food productivity was also calculated separately for the conventional and organic parts of the region to determine the regional organic:conventional yield ratio (OA:CA ratio). To get a more realistic value for the OA:CA ratio, meat production was excluded from this calculation, as this was not related to land-use.

Table 2.2: The area on which each crop is grown in the region of Drenthe in each scenario (ha). Ref = Reference; 25OA = 25% OA; 25OA-FE = 25% OA without feed export; 25OA-MI = 25% OA without manure import; 25OA_E = 25% OA equally distributed.

			Ref	**25OA**	**25OA-FE**	**25OA-MI**	**25OA_E**
Conventional	*Arable*	Starch potato	31,779	30,047	30,047	30,047	24,132
		Sugar beet	17,763	16,796	16,796	16,796	13,489
		Spring barley	10,351	9,787	9,787	9,787	7,860
	Dairy	Silage maize	16,043	10,649	10,649	10,649	12,960
		Grass-clover	61,378	40,742	40,742	40,742	49,581
Organic	*Arable*	Starch potato	2	12	12	12	44
		Spring barley	172	922	922	922	3,485
		Onion	4	23	23	23	87
		Green bean	69	369	369	369	1,394
		Pea	13	69	69	69	261
		Winter rye	488	2,616	2,616	2,616	9,889
	Dairy	Silage maize	277	1,485	1,485	1,485	968
		Grass-clover	5,690	30,511	30,511	30,511	19,879

Table 2.3: Total number of animals for each type of livestock in each scenario. Ref = Reference; 25OA = 25% OA; 25OA-FE = 25% OA without feed export; 25OA-MI = 25% OA without manure import; 25OA_E = 25% OA equally distributed.

		Ref	**25OA**	**25OA-FE**	**25OA-MI**	**25OA_E**
Conventional	Dairy cows	100,257	66,549	66,549	66,549	80,987
	Young stock	67,284	44,662	44,662	44,662	54,351
	Pigs	96,719	96,719	96,719	96,719	96,719
	Poultry	7,712,649	7,712,649	7,712,649	7,712,649	7,712,649
Organic	Dairy cows	3,616	19,390	32,473	31,817	21,158
	Young stock	2,299	12,328	20,647	20,224	13,451
	Pigs	1,451	1,451	1,451	50,862	1,451
	Poultry	148,842	148,842	148,842	5,207,165	148,842

N inputs, outputs and internal flows in the different scenarios were quantified in kg N ha^{-1} and visualised in flow diagrams. The input and output flows were also used to determine N output-input (O/I) ratios and the N cycle count (CyCt). Useful outputs that were considered for the O/I ratio were N in exported food and feed. CyCt indicates the average number of cycles that a nutrient input completes before leaving the region in the form of nutrient losses or exported product. It was calculated from the fraction of nutrients that is lost or removed from the system in each cycle (A) as $(1-A)/A$, as was demonstrated by van Loon et al. (2023).

To quantify total GHG emissions, CO_2, CH_4 and N_2O emissions from the entire region were converted to CO_2-equivalents based on their global warming potential (GWP-100) (Sekiya & Okamoto, 2010). GWP-100 values used for CO_2, CH_4 and N_2O are 1, 28 and 264, respectively. GHG emissions were visualised as emissions per kg food N production and as the total greenhouse gas emissions from each source (e.g. emissions from manure storage, diesel combustion, et cetera).

3 Results

3.1 Regional food production

Organic versus conventional productivity

In all scenarios, organic food productivity was substantially lower than conventional food productivity (i.e. kg N in crop food and dairy per ha of the entire region; Table 3.1). In the reference scenario (Ref), the OA/CA ratio was 0.26 (Table 3.1). The OA/CA ratios of the 25OA, 25OA-FE, 25OA-MI and 25OA_E scenarios are 0.23, 0.38, 0.36 and 0.53, respectively (Table 3.1). Conventional productivity was slightly higher in the scenarios with 25% of the land under OA (139–148 kg N ha^{-1}), compared to the reference scenario (132 kg N ha^{-1}). This was because the conventional area was decreased, while the number of conventional pigs and poultry remained unchanged. Thus, the total regional production of meat remains the same in these scenarios, but this caused the productivity per hectare to be higher.

Regional food productivity in different scenarios

Compared to the reference scenario, total regional food productivity (i.e. combined organic and conventional) was lower in most scenarios with 25% of the land under OA (hereafter: scenarios with 25% OA). In the reference scenario, the total food productivity was 128 kg N ha^{-1} (Figure 3.1a). The total food productivity was slightly lower in the 25OA, 25OA-FE and 25OA_E scenarios (118, 123 and 118 kg N ha^{-1}; Figure 3.1a). The 25OA-MI scenario, which had a larger number of pigs and poultry, was the only scenario in which total food productivity was higher than in the reference scenario (139 kg N ha^{-1}; Figure 3.1a).

Relative change in regional food productivity

As can be seen in Figure 3.1b, total food productivity in the 25OA scenario was 7.7% lower than in the reference scenario. This was due to a reduction in food crop (i.e. plant-based food) and milk production (Figure 3.1b). Compared to the 25OA scenario, food productivity in the 25OA-FE scenario showed a smaller reduction, being only 4.4% lower than in the reference scenario. This was mainly because more of the grass and silage produced in the region was utilised by increasing the number of cattle. The reduction in food productivity in the 25OA_E scenario, compared to the reference scenario, was mainly due to the 12.9% reduction in food crop production, but also due to a slight reduction in milk production (Figure 3.1b). There were no differences in meat production between the reference, 25OA, 25OA-FE and 25OA_E scenarios, as there was no difference in the number of pigs and poultry. Despite lower crop food and dairy productivity, total food productivity in the 25OA-MI scenario was 7% higher than in the reference scenario. This was because meat productivity was 55.2% higher than in the reference scenario (Figure 3.1b).

Organic share of total food production

In the scenarios with 25% OA, the share of organic food in the total food production was not nearly 25% (Table 3.2). This is partly because the number of pigs and poultry in the scenarios 25OA, 25OA-FE and 25OA_E were the same as in the reference scenario, but also largely due to the lower productivity of organic crops and dairy cattle compared to conventional crops and dairy cattle. In addition, a large part of the organic food crops was used as animal feed (i.e. mainly cereals), rather than as food. Because most of the arable organic land was used to grow cereals, this translated into a particularly low organic fraction of food crop production. Although 6.6% of the arable land was under OA in the 25OA, 25OA-FE and 25OA-MI scenarios, only 0.9-1.6% of the exported food crops was organic (Table 3.2). In the 25OA_E scenario, with 25% of the arable land under OA, organic food crops accounted for only 12.8% of the total food crop production. Similarly, whereas 38% of dairy area (i.e. pasture and silage maize) was farmed organically in the 25OA, 25OA-FE and 25OA-MI scenarios and 25% in the 25OA_E scenario, organic milk production did not nearly account for 38% or 25% of the total milk production (Table 3.2). This was mainly due to the lower livestock density on organic pasture.

3.2 Regional feed production

Regional feed production in different scenarios

Regional feed productivity was lower in most scenarios with 25% OA compared to the reference scenario. The total feed productivity in the reference scenario was 161

Table 3.1: Food N productivity (kg N ha^{-1}) of conventional and organic land-based model components (i.e. food crops and dairy) and ratio between the organic and conventional productivity (OA/CA ratio). Ref = Reference; 25OA = 25% OA; 25OA-FE = 25% OA without feed export; 25OA-MI = 25% OA without manure import; 25OA_E = 25% OA equally distributed.

	Conventional productivity kg N ha^{-1}	**Organic productivity** kg N ha^{-1}	**OA/CA ratio** kg N ha^{-1}
Ref	104	27	0.26
25OA	112	25	0.23
25OA-FE	112	43	0.38
25OA-MI	112	40	0.36
25OA_E	102	54	0.53

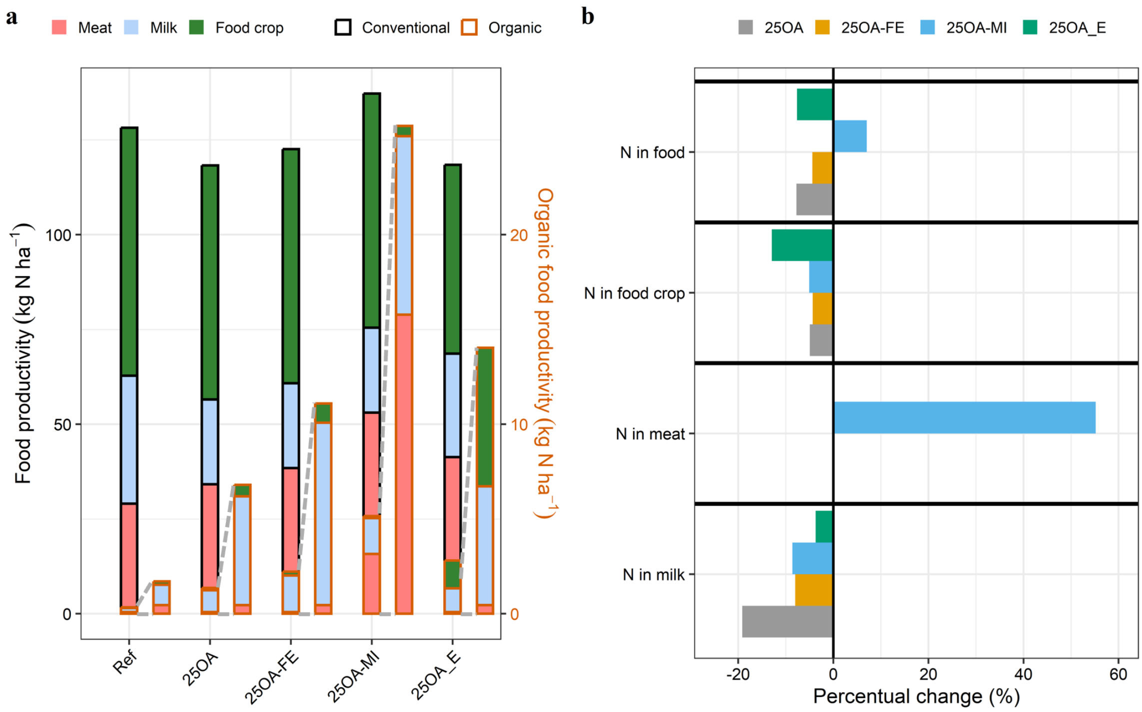

Figure 3.1: (a) Regional conventional and organic food productivity (kg N ha^{-1}). Black bar-outline indicates conventional products and orange bar-outline indicates organic products. Every second bar shows the organic part of the productivity at a five-times scale increase, following the righthand y-axis. (b) Relative change (%) in total food productivity of 25OA scenarios compared to the reference scenario. Ref = Reference; 25OA = 25% OA; 25OA-FE = 25% OA without feed export; 25OA-MI = 25% OA without manure import; 25OA_E = 25% OA equally distributed.

kg N ha^{-1} (Figure 3.2a). Feed productivity was slightly lower in the 25OA, 25OA-FE and 25OA-MI scenarios (150, 152 and 151 kg N ha^{-1}, respectively), but was not notably different in the 25OA_E scenario (157 kg N ha^{-1}; Figure 3.2a). In all scenarios, roughage (i.e. grass-clover) accounted for most of the organic and conventional feed production.

Feed import and export

In all scenarios except 25OA-MI, regional organic feed production was sufficient to meet the feed requirements of organic livestock (Figure 3.2a). In the reference and 25OA scenarios, more organic feed is produced than is required to feed all organic livestock in the region. In the 25OA-FE and 25OA_E scenarios, organic feed requirement is equal to feed production and in the 25OA-MI scenario, feed requirement is substantially higher than feed production. Conventional feed requirement (not shown in Figure 3.2a) is higher than conventional feed production in all scenarios.

Consequently, organic feed was exported in the reference and 25OA scenarios, whereas conventional feed needed to be imported (Figure 3.2b). In the reference

Table 3.2: The share of organic food crops, milk, meat and total food productivity (kg N ha^{-1} of the entire region), including the percentage of the total food production in parentheses (%). Ref = Reference; 25OA = 25% OA; 25OA-FE = 25% OA without feed export; 25OA-MI = 25% OA without manure import; 25OA_E = 25% OA equally distributed.

	Food crop kg N ha^{-1} (%)	**Milk** kg N ha^{-1} (%)	**Meat** kg N ha^{-1} (%)	***Total food*** *kg N ha^{-1} (%)*
Ref	0.2 (0.3)	1.1 (3.1)	0.5 (1.6)	*1.7 (1.3)*
25OA	0.6 (1.0)	5.8 (20.4)	0.5 (1.6)	*6.8 (5.8)*
25OA-FE	1.0 (1.6)	9.6 (28.8)	0.5 (1.6)	*11.1 (9.0)*
25OA-MI	0.5 (0.9)	9.4 (28.4)	15.8 (36.6)	*25.7 (18.6)*
25OA_E	7.2 (12.8)	6.3 (18.7)	0.5 (1.6)	*14.0 (11.8)*

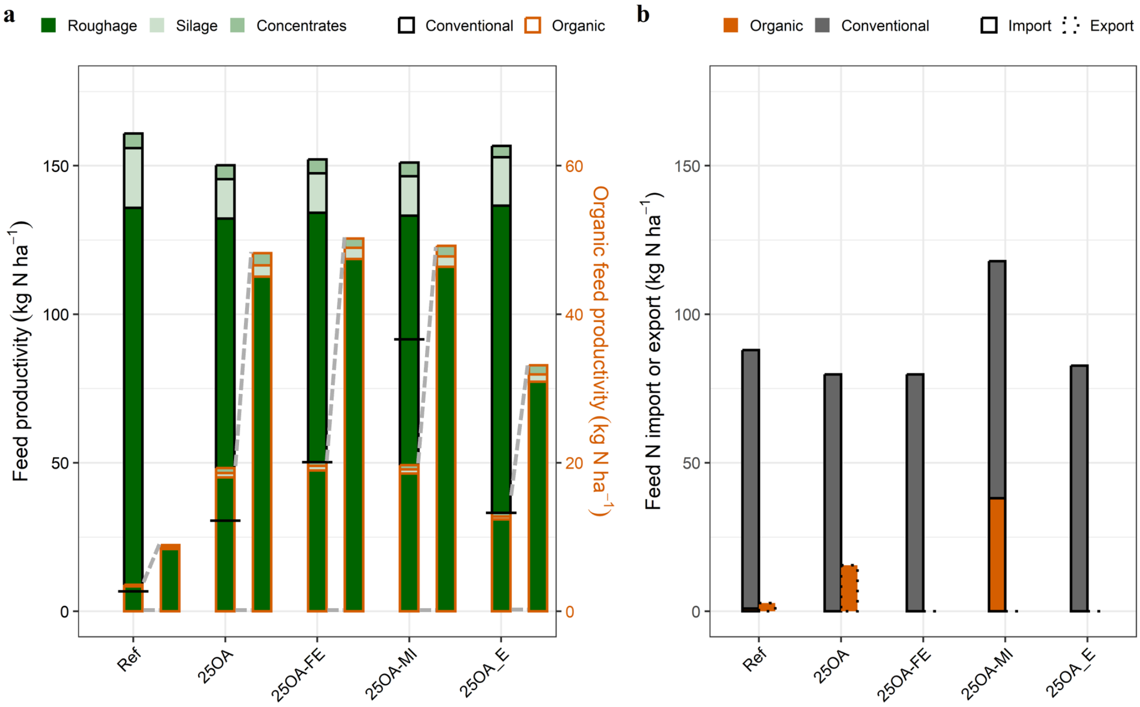

Figure 3.2: (a) Regional conventional and organic feed productivity (kg N ha^{-1}). Black bar-outline indicates conventional feed and orange bar-outline indicates organic feed. Every second bar shows the organic feed productivity at a 2.5-times scale increase, following the righthand y-axis. Black lines crossing the bars indicate the feed requirement of organic livestock. (b) Regional organic and conventional feed N import (left-hand side; solid bar-outline) and export (right-hand side; dashed bar-outline) (kg N ha^{-1}). All imported feed is in the form of concentrates, whereas exported feed can be roughage, silage and concentrates (distinction not shown). Ref = Reference; 25OA = 25% OA; 25OA-FE = 25% OA without feed export; 25OA-MI = 25% OA without manure import; 25OA_E = 25% OA equally distributed.

scenario, 3 kg N ha^{-1} organically produced roughage and silage was exported, 87 kg N ha^{-1} was imported as conventional feed and 1 kg N ha^{-1} was imported as organic feed. In the reference and 25OA scenarios, not all organic roughage and silage was utilised due to the low cattle stocking density, causing this to be exported as organic feed (Figure 3.2b). In the 25OA_E scenario, 5 kg N ha^{-1} was exported as concentrates. In the 25OA-FE and 25OA_E scenarios, organic feed was neither exported, nor imported, as all roughage and silage was utilised by cattle, and the surplus of cereals was used as food instead of feed. In the 25OA-MI scenario, 38 kg feed N ha^{-1} was imported to feed the larger number of pigs and poultry (Figure 3.2b). Conventional feed import was slightly lower in all scenarios with 25% OA, due to the smaller number of conventional cattle compared to the reference scenario.

3.3 Nitrogen cycles and cycling indicators

External N inputs into soil and livestock

Total N inputs did not substantially differ between scenarios, but differences were observed in the amount of soil and feed inputs (Figure 3.3). Most remarkable was the substantially higher input as feed (118 kg N ha^{-1}) and lower soil inputs (183 kg N ha^{-1}) in the 25OA-MI compared to all other scenarios. Furthermore, the proportions of the different sources of soil N inputs differed considerably between the scenarios. Mineral N import was clearly the largest soil N input source in the reference scenario. In the 25OA, 25OA-FE and 25OA_E scenarios, mineral N input was smaller, whereas the N input from manure import and BNF were larger compared to the reference scenario (Figure 3.3).

Regional crop and animal N output

Crop output (i.e. food crop and feed export) is lower in nearly all scenarios with 25% OA, compared to the reference scenario. Only in the 25OA scenario, crop output was substantially higher (78 kg N ha^{-1}) than in the reference scenario (69 kg N ha^{-1}) (Figure 3.3). This increase in crop output was due to a substantially higher feed export (i.e. mainly grass and silage maize) and despite a slightly lower food crop production. The lower crop output in the 25OA-FE, 25OA-MI and 25OA_E scenarios (63, 62 and 57 kg N ha^{-1}, respectively), was due to the lower food crop productivity (Figure 3.3).

Except in the 25OA-MI scenario, animal output (i.e. milk and meat) was lower in all scenarios with 25% OA compared to the reference scenario. In the reference scenario, milk and meat export accounted for an output of 66 kg N ha^{-1} (Figure 3.3). In the 25OA-MI scenario, the animal output was considerably higher (78 kg N ha^{-1}) than in all other scenarios due to more meat production. The animal outputs in the 25OA scenario (58 kg N ha^{-1}) was slightly lower than in the 25OA-FE scenario (63 kg N ha^{-1}). This difference is highlighted because the higher animal output in the 25OA-FE scenario (i.e. 5 kg N ha^{-1} more than the 25OA scenario) did not compensate for the lower crop output (15 kg N ha^{-1} less than the 25OA scenario). This illustrates the inefficiency of feed conversion to milk by cattle.

Soil N pool changes and N losses

Slightly more N was added to the soil N pool in all scenarios with 25% OA (58-60 kg N ha^{-1}), compared to the reference scenario (54 kg N ha^{-1}; Figure 3.3). N losses from the soil, manure storage and crop losses were generally not remarkably different in the scenarios with 25% OA compared to the reference scenario. The only considerable difference was observed in the 25OA_E scenario, where N losses from the soil were slightly higher (75 kg N ha^{-1}) than in the other scenarios (70-72 kg N ha^{-1}).

N cycling and O/I ratio

In general, the scenarios with 25% OA showed a higher CyCt than the reference scenario, but there did seem to be a trade-off between N circularity (i.e. CyCt) and efficiency (i.e. O/I ratio). The O/I ratios in the 25OA and 25OA-MI scenarios were not notably different from that in the reference scenario (Table 3.3). The O/I ratios of the 25OA-FE and 25OA_E were slightly lower (Table 3.3). The CyCts in the 25OA, 25OA-FE and 25OA_E scenarios are higher than in the reference scenario, whereas the CyCt in the 25OA-MI scenario is lower than in the reference scenario (Table 3.3). Interestingly, the 25OA-MI scenario had one of the highest O/I ratios, but the lowest CyCt, whereas the 25OA_E scenario had the lowest O/I ratio and the highest CyCt (Table 3.3).

3.4 Greenhouse gas emissions

Total regional GHG emissions

Total regional GHG emissions per hectare were generally lower in scenarios with 25% OA, compared to the reference scenario. In the reference scenario, the total amount of GHG emissions in the region is 11.2 tonnes (t) CO_2-eq ha^{-1} (Figure 3.4a; Appendix D for precise values). Total GHG emissions in the 25OA, 25OA-FE and 25OA_E scenarios were lower than in the reference scenario, whereas the 25OA-MI scenario was not notably different.

In all scenarios, field emissions (i.e. from applied mineral and organic fertiliser and crop residues), feed import and enteric fermentation cause the majority of GHG emissions (Figure 3.4a). GHG emissions from enteric fermentation, field emissions and mineral N production were slightly lower in all scenarios with 25% OA, compared to the reference scenario. GHG emissions related to manure import are slightly higher in the 25OA, 25OA-FE and 25OA_E, thereby off-setting the reduction in GHG emissions from mineral N production. The amount of GHG emissions from feed import was substantially higher in the 25OA-MI scenario than in any other scenario. In addition, the amount of CO_2-eq from housing is slightly higher in the 25OA-MI scenario, compared to the other scenarios. The amount of CO_2-eq from diesel combustion, pesticide use and indirect N_2O emissions do not notably differ between the scenarios (Figure 3.4a).

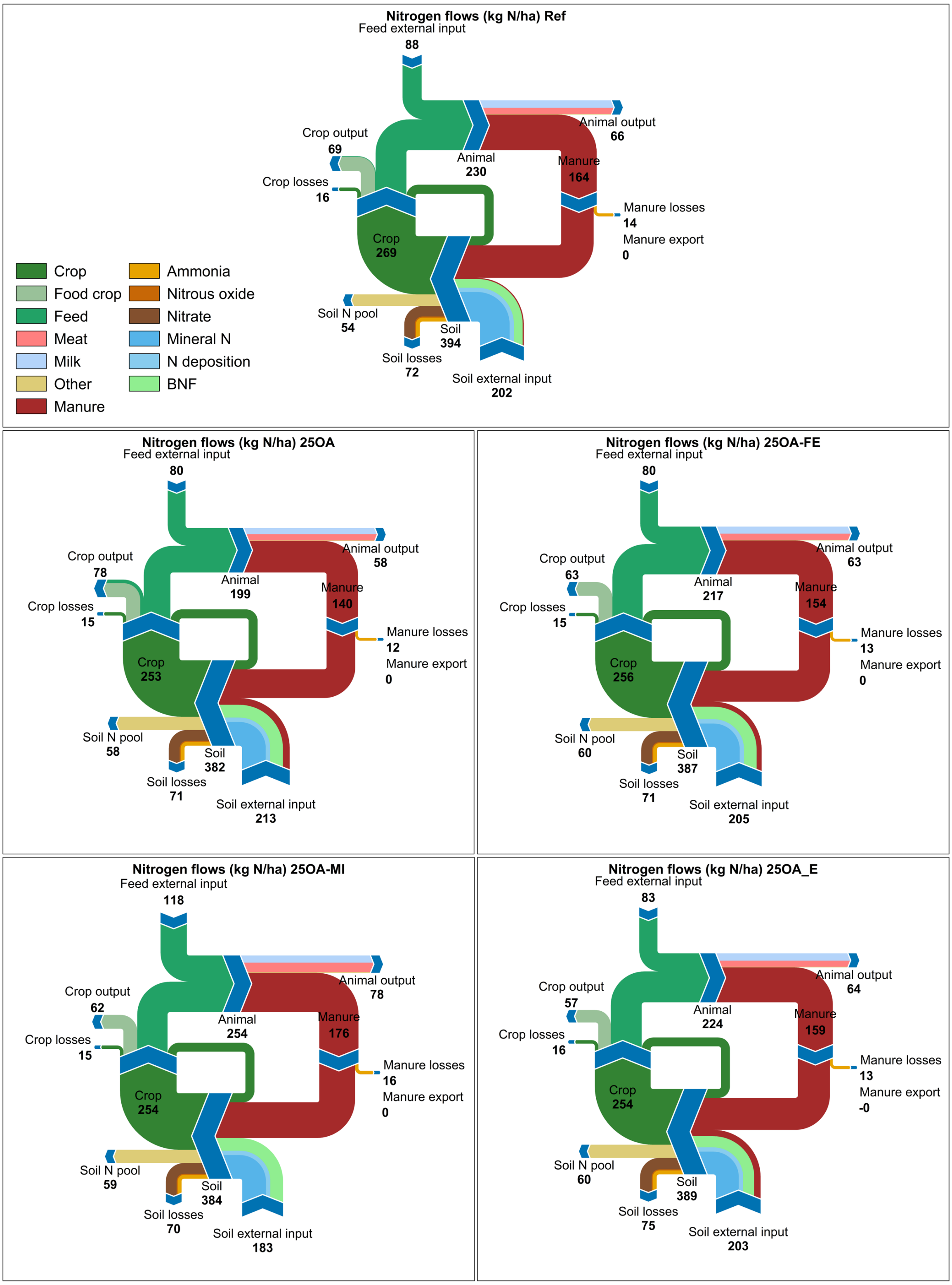

Figure 3.3: Nitrogen flow diagrams showing regional N input, output and intercompartmental flows (kg N ha^{-1}) of all scenarios. No distinction is made between N flows in conventional and organic components. Blue, arrow-shaped nodes indicate N sources, N sinks and model compartments. The colour of the connections between nodes indicate the substance of the flow and the thickness of the connections indicates the flow size. Ref = Reference; 25OA = 25% OA; 25OA-FE = 25% OA without feed export; 25OA-MI = 25% OA without manure import; 25OA_E = 25% OA equally distributed.

Table 3.3: Regional N input and useful output flows (kg N ha^{-1}), N output-input (O/I) ratios and cycle count (CyCt) of the different scenarios. Ref = Reference; 25OA = 25% OA; 25OA-FE = 25% OA without feed export; 25OA-MI = 25% OA without manure import; 25OA_E = 25% OA equally distributed.

	N input kg N ha^{-1}	**Useful N output** kg N ha^{-1}	**O/I ratio**	**CyCt**
Ref	290	134	0.463	0.303
25OA	293	137	0.467	0.316
25OA-FE	285	125	0.440	0.326
25OA-MI	301	140	0.466	0.266
25OA_E	286	121	0.423	0.365

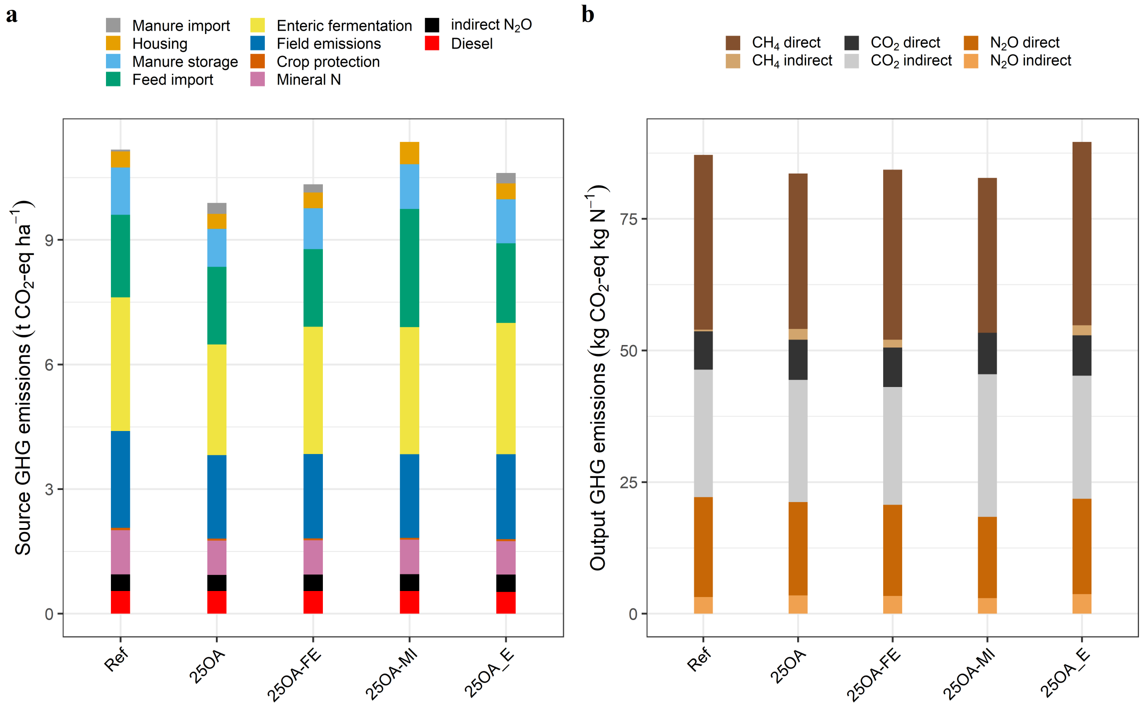

Figure 3.4: (a) Total agricultural GHG emissions in the region, normalised to tonnes CO_2 equivalents per hectare (t CO_2-eq ha^{-1}). Colours indicate the different sources of GHG emissions. (b) N output-corrected GHG emissions in kg CO_2 equivalents per kg food N production (kg CO_2-eq kg^{-1} N). Different colours indicate the contributions of different GHGs (i.e. direct or indirect CO_2, CH_4 and N_2O emissions). Ref = Reference; 25OA = 25% OA; 25OA-FE = 25% OA without feed export; 25OA-MI = 25% OA without manure import; 25OA_E = 25% OA equally distributed.

GHG emissions corrected for food N output

Compared to the reference scenario, the 25OA, 25OA-FE and 25OA-MI scenarios, had lower GHG emissions per kg food N produced, whereas this was higher in the 25OA_E scenario. In the reference scenario, approximately 87 kg CO_2-eq were emitted per kg N in exported product (Figure 3.4b). The emissions per kg N in scenarios 25OA and 25OA-FE are slightly lower than in the reference scenario. Although the total GHG emissions in the 25OA-MI scenario were the highest, the emissions per kg of N were the lowest compared to all other scenarios with 82 kg CO_2-eq kg^{-1} N. In contrast, the emissions per kg N in the 25OA_E scenario are highest with 90 kg CO_2-eq kg^{-1} N, while the total GHG emissions were moderately high compared to the other scenarios. In all scenarios, CH_4 and N_2O emissions were mainly from direct sources, whereas CO_2 emissions were mainly from indirect sources.

4 Discussion

4.1 Reflection on results

Lower food and feed production with higher organic land share

In this study, the effect of increasing the organic land share to 25% on food and feed production was studied. Food N productivity (kg N ha^{-1}) of organically cultivated land was 47-77% lower than that of conventionally cultivated land, depending on the scenario. An analysis by Connor (2022), comparing food productivity of organic and conventional crop and dairy farming at the regional scale in Sweden, showed that organic agriculture produced 26-57% less food (expressed in dry biomass) per hectare than conventional agriculture. Connor (2022) assumed that all feed, for organic and conventional cattle, was produced in the region. This was not the case in my analysis, as there was a shortage of conventional feed, while organic feed production met the feed requirements of organic livestock in most scenarios. Because the area needed to produce conventional feed was excluded from the productivity analysis, the productivity of conventional agriculture was likely overestimated in the current study and the OA:CA ratios were in reality probably more in line with the study by Connor (2022).

Moving to a regional farming system with a higher organic land share with lower productivity would unsurprisingly cause a reduction in total food productivity. Total regional food productivity was lower in the 25OA, 25OA-FE and 25OA_E scenarios and feed productivity was lower in all scenarios with 25% OA, compared to the reference scenario. These results are in line with other studies showing lower field and regional level productivity of organic crops and livestock, compared to conventional (Connor, 2022; de Ponti et al., 2012; Gaudaré et al., 2021). Food production was the lowest in the 25OA_E scenario, where a larger share of the arable land (i.e. 25%) was organically farmed. This highlighted the fact that turning to more organic crop production has a larger impact on food production than more organic dairy production. In the scenario with 25% OA without manure import (25OA-MI), regional food production was higher compared to the reference scenario, but this came with a substantial increase in organic feed import. A large area of agricultural land would be needed to produce enough organic feed outside of the region to feed the organic livestock in the region. This was not accounted for in my study, as this was outside of the system boundary. However, is means that food productivity in the 25OA-MI scenario is lower in reality, and likely also lower than in the current scenario.

Higher share of organic agriculture could improve N circularity

The effect of a higher share of organic land on N losses and cycling and the O/I ratio was also studied. A higher organic land share could contribute to the reduction of N losses, although this depends on the system boundaries. In my analysis, N losses in scenarios with 25% OA were equal to or 2-6% higher, compared to the reference scenario, although the major part of these increased losses was due to an increased flow to the soil N pool. In addition, N losses from the production of imported feed were not considered, because these losses occur outside of the region. Other studies (e.g. Boschiero et al. (2023) and Thomassen et al. (2008)) did consider these "indirect" N losses related to the production of imported feed and thereby found that organic farming systems had lower N losses (i.e. lower eutrophication potential) than conventional systems.

Organic agriculture could contribute to improving regional N circularity, as indicated by the generally higher CyCt values for the scenarios with 25% OA. The N efficiency (as indicated by the O/I ratios) in the scenarios with 25% OA were approximately equal to or slightly lower than the O/I ratio in the reference scenario. Chmelíková et al. (2021) showed that O/I ratios on the farm level are substantially higher on organic farms than on conventional farms. Moreover, O/I ratios at the farm level ranged from 0.77 on conventional arable farms to 0.95 on organic dairy farms (Chmelíková et al., 2021), whereas the regional O/I ratios in my study ranged from 0.423 to 0.467. This large difference in results is likely caused by the fact that my study analysed the entire region, while Chmelíková et al. (2021) identified O/I ratios on the farm level. This highlights the relevance of the chosen system boundaries and scale when determining N cycling and efficiency indicators.

There seems to be a trade-off between N efficiency (i.e. O/I ratio) and N circularity (i.e. CyCt). For instance, the 25OA-MI scenarios showed the second highest O/I ratios (0.466), but the lowest CyCt (0.266) due to the large N input from feed import. The 25OA_E scenario showed the lowest O/I ratio (0.423) but had the highest CyCt (0.365). Indeed, van Loon et al. (2023) found that that a higher O/I ratio does not always lead to a higher CyCt. According to Spiller et al. (2024), this is because the more efficiently N is used (i.e. more N output per N input), the less N remains to recirculate in the system.

This raises the question as to what type of circularity is desirable and what indicator can be useful. The measure of N circularity that was used in this study is a measure of how many times a nutrient circulates through the system (i.e. CyCt). This is likely not the type of circularity that is aimed at by the F2F strategy or that is desirable from a societal perspective. What should be focused on is recycling N streams that are currently lost from the system (i.e. food waste and NH_3, NO_3^- lost to the environment). In order to improve upon these aspects, farming systems could benefit from alternative strategies, like manure digestion, applying composted nature cuttings or recycling food waste into the system. These strategies can help in improving N cycling in both organic and conventional farming systems.

Challenges of achieving self-sufficiency of feed and manure

One aim of this study was to identify possibilities for the organic sector in Drenthe to become more self-sufficient in feed and manure. There are possibilities to reduce imports of feed and manure, but becoming self-sufficient for both feed and manure is more challenging. Thomassen et al. (2008) showed that Dutch organic dairy farms are net importers of roughage, silage and concentrates. It is, however, possible for Dutch organic farming systems to become self-sufficient in feed production (Bos, 2005). My results indeed showed that enough feed could be produced to meet the requirements of organic pigs and poultry. In addition, organic grass-clover and silage maize production in Drenthe were much higher than required to feed organic cattle at the current stocking density (i.e. 0.92 LU ha^{-1} of dairy area (CBS, 2023; Eurostat, 2020)), indicating feed self-sufficiency. Increasing the organic cattle stocking density and thereby utilising all organic roughage and silage, as in the 25OA-FE scenario, could reduce manure import without increasing feed import.

Although a higher cattle stocking density could improve manure self-sufficiency and increase milk production without compromising feed self-sufficiency, it could also have adverse effects. For instance, it should be considered that N losses per unit area can increase, thereby contributing to eutrophication and biodiversity loss (Oudshoorn et al., 2008; Salou et al., 2017). However, my analysis did not show a notable effect of increasing the cattle stocking density (i.e. between the 25OA and 25OA-FE scenarios) on N losses.

Becoming completely self-sufficient for manure would come at the expense of feed self-sufficiency, as more feed needs to be imported. As was pointed out by Migchels et al. (2023), there is a shortage of organic fertiliser to sustain organic crop production. Indeed, large quantities of manure needed to be imported in the scenarios with 25% OA. Only when tremendously increasing the number of organic livestock, no manure import was needed (25OA-MI scenario), but this also required a tremendous increase in organic feed import. Moreover, to produce this feed outside of the region also requires manure for fertilisation. This trade-off between manure and feed self-sufficiency illustrates the challenge of becoming self-sufficient in nutrient supply.

This difficulty is unsurprising, as there is always inevitable removal of N from the system in the form of food, feed, NH_3, N_2O and NO_3^-. N input shortages can partly be compensated by integrating more legumes in the crop rotation (Billen et al., 2021; Ten Berge et al., 2016), but this comes at the cost of an increase in agricultural land requirement (Connor, 2013) and therefore lower total productivity. N losses from leaching and volatilisation can partly be recycled into the system by applying composted organic material from pruning and mowing eutrophicated natural areas, as is already being practiced in the Netherlands (Viaene et al., 2016). N that is lost through export of food could be partly recycled into the system as by applying composted food waste or using food waste as animal feed. However, this is currently not practiced, partly due to strict regulations regarding the use of non-organically certified bioresources (Løes & Adler, 2019; Løes et al., 2017). These strategies for improving circularity were excluded from the current study, but future research could be conducted to analyse their effect on regional nutrient cycles. It should be noted that these strategies can benefit circularity in both conventional and organic systems.

Organic agriculture could help in reducing GHG emissions

Finally, this study aimed to investigate the effect of a higher share of organic land on regional GHG emissions. My analysis showed that scenarios with 25% OA have to potential to emit substantially less GHGs. This supports the findings by Balogh (2023), who found that the increase in organic land-share in the EU has caused a decrease in agricultural GHG emissions in the past decades. Other studies found that the reduction in mineral N fertiliser contributes substantially to the reduction in GHG emissions (Bos et al., 2014; Holka et al., 2022). However, by also considering the emissions related to imported organic manure, my study showed that the reduction of GHG emissions from mineral N fertiliser production is largely offset by the emissions from imported organic manure. When enough organic manure is produced within the region (25OA-MI scenario), the reduction in emissions from imported manure is offset by an increase in emissions from feed import.

Emissions from diesel combustion were not notably different in my analysis. This was unexpected, as diesel use in organic farming is usually considered to be higher due to more mechanical weeding. For instance, Bos et al. (2014) investigated various arable crops and found substantially higher diesel use for organic crops compared to their conventional counterpart. The difference between these results and those in my study is partly caused by the difference in calculating diesel use. Bos et al. (2014) calculated diesel use per cultivation practice and determined for each crop how many cultivation practices were needed, whereas diesel use in my study was based on fixed values from KWIN (2022). In addition, the crops that are part of the organic rotation in my study have generally lower needs in terms of mechanical cultivation practices than the conventional crops.

Even when expressed in CO_2-eq per kg N in exported food, most scenarios with 25% OA have lower GHG emissions. Only in the scenario where 25% of both dairy and arable land are managed organically, the GHG emissions per kg food N was higher than in the reference scenario. This indicates that the lower GHG emissions are mainly due to the lower emissions from organic dairy compared to conventional dairy, while the emissions from organic cropping are higher per unit of product compared to conventional cropping. This is also in line with what was found in multiple studies (e.g. Bos et al. (2014), Flessa et al. (2002), Thomassen et al. (2008)).

Rather small magnitude of differences between scenarios

Overall, the differences between farming systems with 25% OA and the current farming system (reference scenario) were rather small in terms of the indicators food productivity, N cycling and GHG emissions. None of the scenarios with 25% OA showed more than a 10% difference with the reference scenario for any of these indicators, except for N CyCt. The differences were so small because only part of the farming system was altered, namely the land that was converted from conventional to organic between the scenarios (approximately 21% of regional agricultural land). Converting the entire region to organic farming (100% OA), would have shown clearer differences, but as this is a highly unrealistic scenario, it was not included in the current study.

4.2 Considerations and reliability of results

The parameters used in the current study were retrieved from a wide variety of sources, ranging from region-specific to country-wide or even global data sources. The use of more general parameters (i.e. from country-wide or global data sources) likely affected the specificity and reliability of the model outcomes. Even relying on region-specific data could have affected the reliability of the results, because the regional-level model negates, for instance, differences in management between different farmers in the region. Also, conventional data was used for many parameters of organic crops and livestock, since data on organic crops and livestock was often not available. This could have led to inaccurate outcomes for the organic part of the model.

Some aspects of the model were very simplified to make sure that the model was workable. For instance, farmers' decision making about allocating fertiliser to crops was not included, but instead manure application was simply maximised within legal limits or to maximise crop production. Also, the feed quality was not considered in the conversion of feed to meat and dairy. All crop residues were considered to remain on the field, whereas this could in reality also be used as cattle feed or bedding. These simplifications cause the model to be less representative of reality, as is a common feature of modelling at larger scales, like the regional scale in the current study.

The chosen system boundary is highly relevant when analysing the effects of a higher organic land-share on regional productivity, N cycles and GHG emissions. Disregarding N losses, GHG emissions and agricultural land needed to produce animal feed could cause a misinterpretation of results. For instance, the conventional system in my analysis imported much more feed, but the land needed for this was externalised.

4.3 Concluding remarks

When moving to a farming system with a higher organic land share, it is recommended to first focus more on organic dairy production and less on organic arable crop production, judging by the effect it has on food production, N cycling and GHG emissions. Focusing mainly on organic dairy production would have less of a negative impact on food production than having more organic arable crops, because of the generally higher OA/CA ratio of dairy. In addition, GHG emissions per unit of food produced can only be reduced by increasing the share of organic dairy, whereas increasing the share of organic arable land shows an opposite effect. Also from this stance, it is not recommendable to focus on organic pig and poultry production, as organic pigs and poultry are fed with concentrates made from arable crops.

It should be considered that the overall effect of a higher organic land share on regional food productivity, N cycling and efficiency and GHG emissions is small. Although it may have a slightly positive effect on GHG emissions and N cycling, regional food productivity is negatively affected. It can therefore be concluded that moving to a farming system with 25% organic agriculture can contribute only slightly, if at all, to achieving the F2F goals of reducing GHG emissions and N pollution, while safeguarding food production.

4.4 Opportunities for future research

Growing more legumes in the region

One of the main problems encountered in this study was that not enough organic manure was produced in the region to fulfil regional crop N requirements, as was also indicated by several other authors (e.g. Hofstad and Schröder (2002), Migchels et al. (2023), Reimer et al. (2023)). To overcome this shortage, it is often proposed to include more leguminous crops in a rotation Billen et al. (2021). Initially, a scenario with more legumes was included in the current study, but as it showed no clear effect it was decided to remove it from the analysis. The reason for the lack of effect was that the CoPMA model in its current form was unable to account for reduced manure inputs due to the increase in N fixation. This was partly because the model was initially developed to exclusively analyse conventional farming systems. In addition, the model was unable to account for phosphorus (P) inputs. Organic systems that rely more heavily on legumes for N fixation are more prone to P deficits and rely on other P sources (Nelson & Janke, 2007; Smith et al., 2015). For future research, the effect of including more leguminous crops on manure requirements and P cycles would therefore be interesting to study.

Implementing alternative nutrient management strategies

The CoPMA model was initially developed to analyse the effects of different co-product management strategies, both at the farm and regional scale (Vonk et al., unpublished). One of these strategies involved digesting manure prior to application. As the current study does not focus on energy consumption and production, it was decided to leave out the possibility of digesting manure. However, as digestate can also have benefits in terms of nutrient cycling and nutrient use efficiency (Magistrali, 2020), it would be interesting to integrate a scenario with manure digestate. It would also be interesting to investigate the effect of alternative strategies, like applying composted cuttings or food waste, on nutrient cycling. It should, however, be noted that these strategies are not solely applicable to organic farming systems, but could also improve nutrient cycling of conventional farming systems.

Considering effects on biodiversity

One of the main goals of the F2F strategy is to improve biodiversity (EC, 2020). The effect of a higher land-share of OA on biodiversity was, however, not investigated in the current study. In general, organic farming systems are more biodiverse than conventional systems and organic agriculture is therefore concidered to have a positive effect on biodiversity (Bengtsson et al., 2005). However, a recent study by Larsen et al. (2024) showed that spill-over effects cause an increase in pesticide use on neighbouring conventional farms, thereby potentially causing biodiversity loss at the regional scale. Future research could point out the effect of increasing the organic land-share on regional biodiversity in the province of Drenthe.

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Appendix A

Fixed input parameters for animal compartment of the model for conventional (C) and organic (O) animals.

Animal	CO_2-eq imported feed (kg CO_2/kg N)	N intake (kg N)	N retention milk (kg N)	N retention meat (kg N)	N retention other (kg N)	N excretion (kg N)	Milk production (kg milk)	Fraction TAN (kg N/kg N)	Enteric fermentation non-cow (kg CH_4/ animal)	CH_4 conversion cow (kg CH_4/MJ energy)	EF CH_4 manure storage (kg CH_4/animal)	EF NH_3 manure storage (fraction of TAN)	EF NH_3 grazing (fraction of TAN)
Dairy cattle (C)	13.3	195.1	48.5	0.0	0.9	145.7	8674.0	0.56	*NA*	0.0573	38.99	0.146	0.04
Young cattle (C)	13.3	42.4	0.0	0.0	4.2	38.2	0.0	0.59	*NA*	0.0582	7.93	0.143	0.04
Pig (C)	32.8	14.5	0.0	5.2	0.0	9.3	0.0	0.67	1.5	*NA*	5.73	0.167	*NA*
Laying hen (C)	24.8	1.09	0.0	0.445	0.007	0.6	0.0	0.68	0.0	*NA*	0.03	0.176	*NA*
Dairy cattle (O)	13.3	171.7	42.7	0.0	0.8	128.2	7633.1	0.56	*NA*	0.0573	23.21	0.146	0.04
Young cattle (O)	13.3	37.3	0.0	0.0	3.7	33.6	0.0	0.59	*NA*	0.0582	4.72	0.143	0.04
Pig (O)	32.8	12.8	0.0	4.6	0.0	8.2	0.0	0.67	1.5	*NA*	5.73	0.167	*NA*
Laying hen (O)	24.8	1.0	0.0	0.4	0.006	0.6	0.0	0.68	0.0	*NA*	0.03	0.176	*NA*

Appendix B

Fixed input parameters for manure storage compartment of the model used for conventional (C) and organic (O) farms.

Manure type	WC_org (fraction)	WC_min (fraction)	Mineral N (kg N/Mg FM manure)	Total N (kg N/t FM manure)	Total P (kg P/t FM manure)	DM (kg DM/t FM)	EF N_2O storage (kg N_2O-N/kg N in manure)	EF N_2O grazing (kg N_2O/kg N in manure)	OM content (kg OM/t FM manure)	Humification coefficient (fraction of OM)
Dairy slurry (C & O)	0.13	0.95	2.0	4.1	0.655	85	0.002	0.006	64	0.7
Pig slurry (C)	0.496	0.95	4.6	7.1	2.009	93	0.002	*NA*	43	0.33
Chicken solid manure (C & O)	0.5	0.8	2.5	25.6	8.559	573	0.001	*NA*	416	0.33
Pig solid manure (O)	0.496	0.8	1.2	7.6	2.842	230	0.002	*NA*	160	0.33

Appendix C

Fixed input parameters for different conventional (C) and organic (O) crops. b_0, b_1 and b_2 indicate coefficients for N response curves ($yield = b_0 + b_1x + b_2x^2$ with x = effective N application in kg N).

Crop	b_0	b_1	b_2	OA:CA yield ratio	BG residue: product (kg DM/kgDM)	Aboveground residue intercept	Aboveground residue slope	N in product (kg N/t DM product)	DM product (kg DM/kg FM)	N in AG residue (kg N/kg DM)	N in BG residue (kg N/kg DM)	C:N ratio residues (kg C/kg N)	Humification coefficient residues (fraction)	Diesel use (L/ha)	Max. effective N application	EF NH_3 residues	BNF (kg N/ha)	Crop protection CO_2-emission (kg CO_2-eq)
Starch potato (C)	10.8	0.027	-5.0E-05	*NA*	0.20	1.06	0.10	15.9	0.252	0.019	0.014	16	0.22	234	230	0.003	0	60
Sugar beet (C)	13.6	0.071	-2.3E-04	*NA*	0.20	1.06	0.10	5.0	0.229	0.019	0.014	22	0.21	117	145	0.0072	0	60
Spring barley (C)	3.30	0.064	-2.5E-04	*NA*	0.22	0.75	1.29	16.7	0.827	0.007	0.014	68	0.32	124	80	0	0	60
Silage maize (C)	10.4	0.038	-1.0E-04	*NA*	0.22	0.00	0.30	13.0	0.315	0.006	0.007	58	0.33	124	140	0	0	60
Grass-clover (C)	7.70	0.020	-1.6E-05	*NA*	0.80	0.00	0.30	25.3	0.160	0.015	0.012	24	0.29	174	250	0	80	60
Green bean (O)	1.24	0.002	-1.6E-06	0.91	0.19	0.85	1.09	36.3	0.106	0.008	0.008	20	0.23	167	110	0	54.4	2
Pea (O)	2.77	0.028	-1.4E-04	0.85	0.19	0.85	1.09	52.5	0.811	0.008	0.008	15	0.22	82	30	0	64	2
Winter rye (O)	2.27	0.022	-6.3E-05	0.76	0.22	0.88	1.09	22.4	0.827	0.005	0.011	75	0.31	89	140	0	0	2
Spring barley (O)	2.28	0.044	-1.7E-04	0.69	0.22	0.59	0.98	16.7	0.827	0.007	0.014	68	0.31	98	80	0	0	2
Starch potato (O)	7.55	0.019	-3.5E-05	0.70	0.20	1.06	0.10	15.9	0.252	0.019	0.014	16	0.22	325	230	0.003	0	2
Onion (O)	4.16	0.031	-8.7E-05	0.77	0.22	1.06	0.10	15.9	0.113	0.008	0.009	20	0.21	238	120	0	0	2
Silage maize (O)	8.88	0.033	-8.5E-05	0.85	0.22	0.61	1.03	13.0	0.315	0.006	0.007	58	0.33	146	140	0	0	2
Grass-clover (O)	6.85	0.018	-2.1E-04	0.89	0.80	0.00	0.30	25.3	0.160	0.015	0.012	24	0.29	174	250	0	160	2

Appendix D

GHG emissions from each individual source (t CO_2-eq ha^{-1}) and the relative contribution of each source to the total emissions (%).

	Ref	25OA	25OA-FE	25OA-MI	25OA_E
Manure import	0.05(0.4%)	0.27 (2.7%)	0.2 (1.9%)	0 (0%)	0.25 (2.4%)
Housing	0.38 (3.5%)	0.36 (3.7%)	0.38 (3.7%)	0.54 (4.7%)	0.38 (3.6%)
Manure storage	1.14 (10.3%)	0.91 (9.3%)	0.99 (9.6%)	1.08 (9.5%)	1.06 (10%)
Feed import	1.98 (17.8%)	1.87 (19%)	1.87 (18.1%)	2.84 (25.1%)	1.92 (18.1%)
Enteric fermentation	3.22 (29%)	2.66 (27.1%)	3.06 (29.8%)	3.06 (27%)	3.16 (29.9%)
Field emissions	2.33 (21%)	2.01 (20.4%)	2.03 (19.7%)	2.01 (17.8%)	2.05 (19.4%)
Crop protection	0.06 (0.5%)	0.05 (0.5%)	0.05 (0.4%)	0.05 (0.4%)	0.05 (0.4%)
Mineral N import	1.06 (9.6%)	0.83 (8.4%)	0.83 (8.1%)	0.83 (7.3%)	0.81 (7.7%)
Indirect N_2O	0.4 (3.6%)	0.39 (3.9%)	0.4 (3.8%)	0.41 (3.6%)	0.42 (3.9%)
Diesel combustion	0.55 (4.9%)	0.55 (5.5%)	0.55 (5.3%)	0.55 (4.8%)	0.52 (5%)