Modelling organic farming systems:

Is livestock needed for a functioning nitrogen cycle and food production?

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Master degree project • 30 credits
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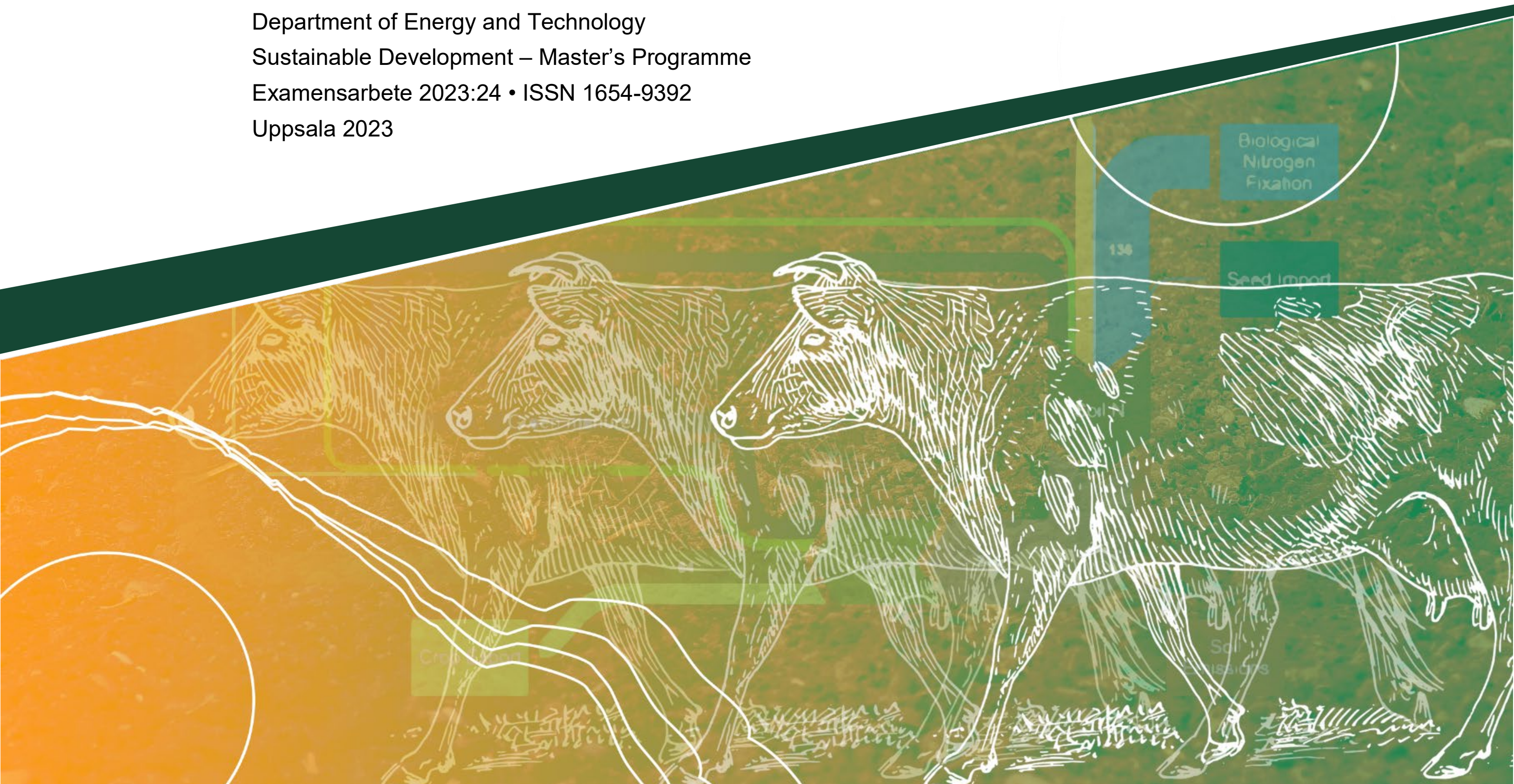
Faculty of Natural Resources and Agricultural Sciences
Department of Energy and Technology
Sustainable Development – Master’s Programme
Examensarbete 2023:24 • ISSN 1654-9392
Uppsala 2023



Modelling organic farming systems: Is livestock needed for a functioning nitrogen cycle and food production?

Modellering av ekologiska jordbrukssystem: Behövs djur för en fungerande kvävecykel och mat produktion?

Franziska Johanna Galler

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Credits:	30 credits
Level:	Second cycle, A2E
Course title:	Master thesis in Environmental Science, A2E – Master's Programme Sustainable Development
Course code:	EX0901
Programme/education:	Sustainable Development – Master's Programme
Course coordinating dept:	Department of Aquatic Science and Assessment
Place of publication:	Uppsala, Sweden
Year of publication:	2023
Cover picture:	By Anna Fath 2023
Copyright:	All featured images are used with permission from the copyright owner.
Title of the Series:	Examensarbete (Institutionen för energi och teknik, SLU)
Part number:	2023:24
ISSN:	1654-9392
Keywords:	organic farming, livestock, stockless farming, nitrogen cycle, nitrogen use efficiency, nitrogen recycling, nutritional value, human nutrition, food system

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Abstract

Livestock has always been an integral part of nutrient management on organic farms. Environmental, economic and idieological trends are leading to an increasing specialization of agriculture away from mixed farms with livestock. The viability of stockless organic farms has mostly been researched from a nutrient/nitrogen management perspective, with conflicting results on nutrient supply, leading to the question of whether or not livestock is needed.

This work is therefore among the first to address this question from a food system perspective. First the nitrogen cycle of two farms (stocked and stockless) was modelled based on real farm data (Hülsbergen 2022), and optimized for a maximum nitrogen output for human consumption (crop and livestock products), while maintaining a balanced nitrogen budget for fair comparability.To answer what role livestock has in sustaining the nitrogen cycle on organic farms, the two farming systems were compared based on nitrogen flows, nitrogen use efficiency, nitrogen recycling rate, total emissions and net food production. In a second step, each farming model was optimised in three scenarios to achieve maximum crude protein, energy and fat output, to see how efficient stockless farming systems are at providing macronutrients compared to stocked farming systems. To make these figures more concrete, the supported human population per farm was calculated on the basis of nutritional requirements of an adult.

The stockless farm had a more efficient nitrogen utilization in terms of food production than the stocked, but this could be reversed if nitrogen emissions were better mitigated during storage and application of livestock manure. The optimal livestock density was rather extensive at 0.46 LU ha^{-1}, but organic fertilizer, whether from livestock or biogas plant, was of rather minor importance for the nutrient supply of the soil compared to biological nitrogen fixation. In terms of nutritional energy supply outperformed the stockless system the stocked, which was the opposite for fat. Protein supply was close in both systems with a tendency to a higher supply in the stocked system when including the sensitivity analysis. Overall, fat was the limiting factor when considering a full diet, as it supported in all scenarios the least number of individuals. The stocked system supported eight individuals per ha and year, while the stockless system supported seven individuals, which makes both system quite similar in terms of food provision.

This work should be seen as a fragment of a holistic approach to the question whether livestock is needed for organic agriculture or not, as it does not take into account all important nutrients. Nitrogen, however, is the limiting nutrient for growth, and thus forms a valuable starting point to this holistic apporach. The work has shown that livestock production is not redundant, but that stockless systems nevertheless have their advantages from a nitrogen management perspective. It is particularly important to which stockless recycling pathway livestock production is compared to, as composting might be less efficient than a biogas plant and livestock as nitrogen recycler. From a food provision perspective has the stockless system on first sight a more efficient and therefore higher macronutrient production. When fat is considered as a limiting factor in the overall diet, livestock can be seen beneficial to a farming system as a net producer of fat.

Keywords: organic farming, livestock, stockless farming, nitrogen cycle, nitrogen use efficiency, nitrogen recycling, nutritional value, human nutrition, food system

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Abbreviations

AG	Above ground crop residues
BG	Below ground crop residues
BR	Body retention rate
C	Corn
CH_4N_2O	Urea
CP	Crude Protein
FAO	Food and Agriculture Organization of the United Nations
IFOAM	International Federation of Organic Agriculture Movements
IPCC	Intergovernmental Panel on Climate Change
LfL	Bavarian State Research Center for Agriculture
LfULG	Saxony State Office for Environment, Agriculture, Geology
LtZ	Augustenberg Agricultural Technology Center
LU	Livestock units (1 LU = 500 kg living weight)
MJ	Megajoules
N	Nitrogen
N_2	Dinitrogen
NFSA	Norwegian Food Composition Database
NH_3	Ammonia
NH_4^+	Ammonium
NLP	Net livestock production
NO_2^-	Nitrite
NO_3^-	Nitrate
NOx	Nitrogen Oxides
N_2O	Nitrous Oxide
O	Oat
P	Potato
UBA	German Environment Federal Office
USDA	United States Department of Agriculture
WHO	World Health Organization
wW	Winter wheat

1. Introduction

The close relationship between agricultural productivity and livestock can be traced back as far as the year 6000 BC (Bogaard et al. 2013). Even today, livestock is still considered vital to a sustainable future food system because of its contribution to the cycle of nutrients and other resources on farm (Poux & Aubert 2018; Van Zanten et al. 2019; Karlsson 2022). Van Zanten et al. (2019:20) emphasize "use animals for what they are good at", referring to the recycling of by-products and biomass from leys and pastures. The nutrients contained in this biomass would otherwise be lost - not only for human consumption, but also for agricultural production. A key characteristic of livestock is that their manure contributes to the transfer of nutrients from areas where nutrients accumulate, for example by cultivating legumes, to areas where nutrients get exported, such as fields where cash crops are grown (Poux & Aubert 2018). In particular, nutrient management in organic farming is building on this mechanism, which makes this type of agricultural system to a high degree dependent on livestock (Watson et al. 2002; Foissy et al. 2013; Nowak et al. 2015; Barbieri et al. 2021; Schulz 2021).

At the same time, livestock production is in critique for its inefficient use of resources and large environmental footprint, putting pressure on the planet and its boundaries (Campbell et al. 2017). Livestock production uses approximately 40% of the world's arable land for feed (Mottet et al. 2017), 32% of freshwater is consumed by farmed animals (Herrero et al. 2016), and it is responsible for up to 16.5% of total anthropogenic greenhouse gas emissions (Twine 2021). From a food supply perspective, animals are also not particularly efficient at utilizing and providing protein and energy (Ritchie et al. 2018), and are therefore accurately described by Karlsson (2022:13) as “a net sink […] for macro- and micronutrients”. According to Ritchie et al. (2018) and van Zanten et al. (2016), it is consequently more efficient for crops to be consumed directly by humans than to feed them to animals first.

There are several approaches for reducing the impact of livestock production on the planet. The overarching call is that industrialized, high income nations must reduce meat consumption - and thus production - by at least 75% in order to effectively reduce the environmental impact of agricultural production (Parlasca & Qaim 2022). As the spirit of times demands, farms - including organic ones - are evolving towards greater specialization, without livestock (Watson et al. 2002; Råberg et al. 2018; Biernat et al. 2020). Freytag et al. (2023) even claim that stockless organic farming is key to Germany's goal of 30% organic farmland by 2030, which was set by the current government as an incentive for sustainable land use change (SPD et al. 2021). The reasons for stockless specialization may be ideological (Seymour & Utter 2021), but also of economic and organizational origin (Schmidt 2003). As Freytag et al. (2023) summarize, incentives to specialize in crop production are that livestock production is associated with high investment requirements, high labor costs, and complicated legislation. But mobile fertilizer in form of manure is not always available for all farms, whether for ideological reasons of strictly avoiding any animal input (Seymour & Utter 2021), or for organizational reasons of not being able to cooperate with livestock farms (Borgen et al. 2012; Råberg et al. 2018). Therefore, the efficiency of organic nutrient cycles without livestock is questionable in the context of organic nutrient management principles. Some research found nutrient or fertility deficiencies in stockless organic rotations (Berry et al. 2003; Colomb et al. 2013; Foissy et al. 2013), some found it to be even more productive than conventional ones when including biogas digestate (Chmelíková et al. 2021; Freytag et al. 2023). So do we need livestock for sustainable organic agriculture or not?

To investigate long term viability of farms, much of the research to date has focused on nutrient cycles, budgets, and efficiency, as nutrient management is one of the key screws of system sustainability in agriculture (Watson et al. 2002; Berry et al. 2003; Goulding et al. 2008; Küstermann et al. 2010; Nowak et al. 2013; Lin et al. 2016; Mu et al. 2016; Einarsson 2017; Råberg et al. 2018; Chmelíková et al. 2021; Wivstad et al. 2023). Typically, nutrient mass flows and yields are used as the basis for comparison in research like this (Willoughby et al. 2022). But from a food systems perspective, this approach only represents the environmental efficiency of an agricultural system, not what it actually provides for: human nutrition (Röös et al. 2021). Willoughby et al. (2022) points out that yield does not automatically indicate nutritional value, as it varies from crop to crop, as does the composition of crops on different farms. Cassidy et al. (2013) and Röös et al. (2021) therefore suggest expressing yield in terms of "people fed per hectare" to reflect the true food production performance per farm as a complement to resource efficiency assessments. Willoughby et al. (2022) are among the first to combine nutrient budgeting with food value to develop an indicator of nutrient use efficiency of macronutrient production. However, they focused more on comparing conventional and organic nutrient management practices.

Organic farming is a promising alternative to high input agriculture. At the same time, one of the main pillars of organic agriculture, livestock production, is being challenged by the complex conflicts of our food system outlined above. This thesis therefore addresses the following questions with a focus on nitrogen:

What is the role of livestock in sustaining nitrogen circulation in organic farming systems? How efficient are stockless organic farming systems in terms of human nutrition compared to stocked organic farming systems?

Modelling the nitrogen cycle of an organically managed farm with and without livestock will provide insight into the impact of livestock on the on-farm nitrogen flows. The approach is to optimize each model to maximize nitrogen output while maintaining a balanced nitrogen budget, and to compare these system models based on nitrogen flows, nitrogen use efficiency, nitrogen recycling rate, total emissions, and net food production. In a second step, each model is optimized in three scenarios according to one macronutrient each (crude protein, energy and fat) to broaden the discussion on the need for livestock not only at the farm system level but also on a food system one to secure human nutrition.

2. Background

Agricultural production is the main driver of the nitrogen cycle (Campbell et al. 2017), which intertwines the two closely. The invention of industrial ammonia synthesis for production of nitrogen fertilizer tripled agricultural food production only in the last half century, but also introduced new burdens for environment and human health (Moiser et al. 2004; Campbell et al. 2017). Knowledge about both systems is therefore key for sustainable food production in all ways – for farmers, the society and the environment. The following sections highlight the fundamentals of both, the agroecological nitrogen cycle and organic farming systems.

2.1 Nitrogen cycle

The natural nitrogen cycle is one of many nutrient cycles on earth, but one of the most essential one. Nitrogen can be found in a variety of organic compounds, for example in form of amino acids, proteins, and nucleic acids (Martin & Sauerborn 2013; Einarsson 2017) and is thus the limiting driver for growth (von Liebig 1862; Moiser et al. 2004).

Figure 1 on page 13 provides an overview of nitrogen flows and processes in an agricultural system. Soil holds nitrogen in various forms, where some of them can be taken up by plants. Both animals and humans use these plants to live, while in the case of animals, the unused nitrogen returns to the soil in the form of excreta. Human consumption is in terms of nutrient recycling a dead end for agricultural production (Goulding et al. 2008). The problem is called nutrient mining, describing the disconnection of where the nutrients are produced and where they are consumed, enhanced through urbanisation (Jones et al. 2013; Ball et al. 2018; Gwara et al. 2021). Gwara et al. (2021:2) claim that up to 70% of soil nutrients are lost as waste through the “mine, excrete and flush down the end-of-pipe centralized sewer system”- system. Crop residues, green manure, compost, biogas digestate and animal manure are currently the only way to return recycled nutrients such as nitrogen to the soil. There are natural processes such as biological nitrogen fixation and atmospheric nitrogen deposition that add "new" nitrogen to the soil and the farming system (see subsection 2.1.1), or synthetic fertilizers as used in conventional farming systems. The difference to the recycled nitrogen inputs is that synthetic fertilizer adds additional new nitrogen to the system. It also does not return and therefore maintain organic matter in soil (Johnston et al. 2009; Ladha et al. 2011). Soil organic matter is the key to soil fertility, nutrient retention, and other physical soil properties such as soil structure and water-holding capacity (Johnston et al. 2009; Ladha et al. 2011). The mineralization of soil organic matter makes nitrogen and other nutrients available to plants, completing the cycle (Johnston et al. 2009; Ladha et al. 2011).

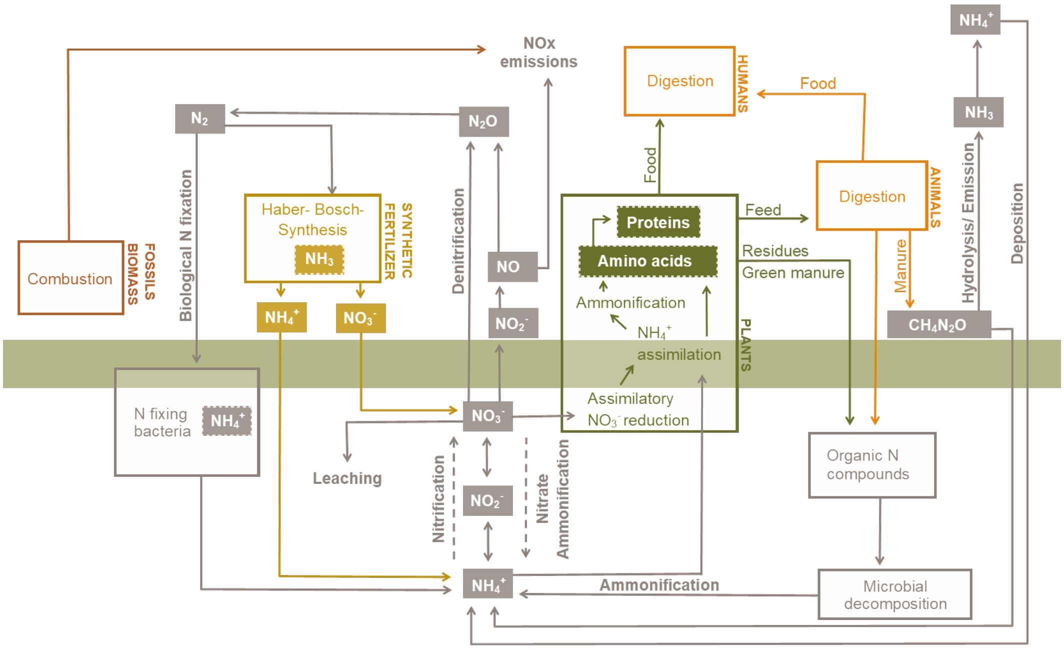

Figure 1 Agroecological nitrogen cycle. *Plants feed from nitrogen held in the soil, and are either used as food or feed for humans and animals. Animal manure, crop residues or green manure are ways to recycle nitrogen. Biological nitrogen fixation, nitrogen deposition, and synthetic fertilizers add additional nitrogen to the soil. Natural processes cause nitrogen emissions in different stages and several forms. The figure was adapted and adjusted from Martin and Sauerborn (2013).*

The agroecological nitrogen cycle will never be a closed system, since in addition to nutrient export, emissions will always occur through natural processes. The following subsections highlight all these relevant processes within the agroecological nitrogen cycle.

2.1.1 Nitrogen fixation

Atmospheric nitrogen (N_2) is the most abundant element in the atmosphere. In this form, however, it is not usable by animals or plants, which is why there are processes to convert it to, for example, plant-available nitrate (NO_3^-) or ammonium (NH_4^+) (Martin & Sauerborn 2013). The formation of these nitrogen compounds can occur in three main ways: two natural, atmospheric deposition and biological nitrogen fixation, and one industrial, the Haber-Bosch synthesis (Martin & Sauerborn 2013).

Atmospheric deposition

Figure 1 shows parts of the process of atmospheric nitrogen deposition. As described by Martin and Sauerborn (2013) lightning strikes release energy which can split the inert nitrogen molecules. That way N_2 is converted by various reactions with water and oxygen to compounds like nitrous acid, nitric acid, nitrite (NO_2^-) as well as NO_3^- (Martin & Sauerborn 2013). However, the majority of the deposited atmospheric nitrogen comes from NH_3 and nitrogen oxides (NO_x) emitted from agricultural, biological and other sources (Le Noë et al. 2018). The amount of nitrogen deposited annually from the environment can vary by region, but also by livestock density (Le Noë et al. 2018). Martin and Sauerborn (2013) assume a deposition of 10 to 30 kg N ha^{-1} a^{-1} in central Europe. Einarsson et al. (2018) had an average atmospheric nitrogen deposition of 6 kg N ha^{-1} a^{-1} on Swedish organic dairy farms, Hülsbergen et al. (2022) assumed a blanket deposition of 20 kg N ha^{-1} a^{-1} in their German farm system modelling.

Biological nitrogen fixation

Biological nitrogen fixation involves bacteria capable of reducing N_2 to ammonia (NH_3) and NH_4^+ (Martin & Sauerborn 2013). These bacteria are either free-living, utilizing organic compounds and releasing them as nutrients when concentrated near specific plant rhizospheres, or are in symbiotic relationships with other organisms (Martin & Sauerborn 2013). The bacteria only enter into this symbiosis with legumes, which form microcolonies, also called root nodules within the plant roots (Martin & Sauerborn 2013). These symbiotic nitrogen fixers receive then carbon compounds from their host plant, while the host plant benefits from the supply of fixed nitrogen (Martin & Sauerborn 2013). Estimates of nitrogen fixation potential vary widely. Depending on the species, nitrogen symbiotically fixed by rhizobia on legume shoots can range from 0 to 450 kg N ha^{-1} (Unkovich & Pate 2000; Anglade et al. 2015).

Haber-Bosch synthesis

The Haber-Bosch synthesis is used for synthetic fertilizer production. Atmospheric nitrogen is made to react with hydrogen using high pressure, high temperature and a catalyst to produce NH_3 (Martin & Sauerborn 2013). NH_3 can then be further processed into a variety of other commercial fertilizers, such as urea (Martin & Sauerborn 2013). According to Martin and Sauerborn, this invention is the largest contribution to the anhtropogenic modification of the nitrogen cycle.

2.1.2 Soil - plant processes

As indicated in Figure 1, NH_4^+ can enter the soil from the environment, as a synthetic fertilizer, or as a result of *ammonification* which is the ultimate step in decomposition of organic compounds microorganisms. Ammonification is one of the main processes of nitrogen mineralization, which basically stands for the decomposition process of all organic matter added to the soil. Back to the released NH_4^+, in the presence of oxygen, microorganisms oxidize NH_4^+ to NO_2^- and in a further step to plant-available NO_3^-. This process is called *nitrification* (see Figure 1). From this point on, NO_3^- can take one of two paths. When absorbed by a plant, all mineralization is reversed to convert the NO_3^- into an organic nitrogen compound of the plant organism, like amino acids (green box in Figure 1). Alternatively, it can be converted back to NH_4^+ by certain bacteria in the soil, if it is not taken up by a plant and needs anaerobic, wet and acidic conditions. This reversal via NO_2^- is called *nitrate ammonification*. (Martin & Sauerborn 2013; Einarsson 2017)

2.1.3 Nitrogen emissions

Common forms of nitrogen losses to the atmosphere or water are NH_3, NO_3^-, nitrous oxide (N_2O) or NO_X. The pathways by which these emissions occur are described below, arranged by emitted product.

Ammonia

About 80% of the total NH_3 emissions in Europe are caused by animal manure management, mainly during storage and application to soil (Oenema et al. 2003). But it is not just the application of animal manure; synthetic fertilizers and biogas digestates also add to the global NH_3 emissions (Ma et al. 2021; Pedersen & Hafner 2023). NH_3 is mainly emitted by the *hydrolysis* of urea (CH_4N_2O, Figure 1), which is present in liquid and solid manure, digestate or synthetic fertilizers (Martin & Sauerborn 2006). NH_3 is a driver for acid rain and for smog formation through aerosols and indirect for terrestrial eutrophication after NH_3 deposition (Einarsson 2017; Fagodiya et al. 2020).

Nitrate

Nitrate is beside bacteria and other microbes, to a large extent taken up by plants. When there is an excess, for example due to excessive fertilization, NO_3^- is leached into ground and surface water. There it can become toxic for human consumption or cause eutrophication. Excessive nutrient levels in surface waters cause algal blooms, which can turn the water into an oxygen-deficient state, a dead zone for most aquatic life. Leaching depends on the amount of fertilizer applied as well as the climate, soil type and crop stand, with more leaching occurring in winter because plants and microorganisms are not as active as in summer. (Martin & Sauerborn 2006)

Nitrogen oxides and nitrous oxide

The process of converting NO_3^- to N_2, called *denitirificaiton*, is favoured in anaerobic conditions, high temperature, as well as high soil carbon and nitrate contents

(Martin & Sauerborn 2006; Fagodiya et al. 2020). The conversion proceeds through NO_2^-, NO and N_2O, releasing N_2O and other nitrogen oxides into the atmosphere if reduction is not complete (Martin & Sauerborn 2006; Fagodiya et al. 2020). N_2O is a potent greenhouse gas that contributes to global warming and ozone depletion, while NO_x contributes to air pollution through smog and acid rain (Einarsson 2017; Fagodiya et al. 2020). Oenema et al. (2003) mention that about 50% of total agricultural N_2O emissions in Europe are caused by manure management, but much is also related to inappropriate use of any fertilizers on agricultural soil (Einarsson 2017; Fagodiya et al. 2020). NO_x emissions are mainly caused by combustion of organic matter and fossil fuels (Einarsson 2017; Fagodiya et al. 2020).

2.2 Organic agriculture

The European umbrella organisation for organic food and farming, IFOAM, provides a commonly used definition of organic agriculture principles. Fundamental principles like the preventive avoidance of synthetic fertilizers, pesticides, animal drugs, and food additives are regulated and certified by the European Union (European Union 2018; Lorenz & Lal 2023). Another important element is area-based animal production (European Union 2018).

> "Organic Agriculture is a production system that sustains the health of soils, ecosystems, and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather the use of inputs with adverse effects. Organic Agriculture combines tradition, innovation, and science to benefit the shared environment and promote fair relationships and good quality of life for all involved."
>
> (IFOAM General Assembly 2008)

Based on this definition, organic farmers follow the central philosophy of a selfsustaining unit by reducing the external inputs while reusing and recycling materials and nutrients on farm, as well as managing energy use in an efficient way (Kirchmann & Bergström 2008; Lorenz & Lal 2023). The organic movement therefore seeks to be the sustainable, circular counterpart to linear, input-intensive conventional farming (Vermeyen et al. 2021; IFOAM Organics Europe 2023). However, a complete circularity of materials is not realistic (Kirchmann & Bergström 2008; Van Zanten et al. 2019).

As in conventional agriculture, farming systems in organic agriculture can be categorized as mixed farms, or as specialized farms either on stockless crop production, livestock or horticultural production (Watson et al. 2002). As mentioned in the introduction, there is a trend towards more specialization. However, in addition to political and economic reasons, there may also be an ideological driver behind it, namely vegan production principles that claim to go "beyond organic"(Seymour 2018). Since 2017, farms can be certified according to biocyclic - vegan standards and thus commit themselves to a purely plant-based production method, with no commercial livestock production for any kind of human utilization but also any other animal derived farming inputs (Adolf Hoops Society 2020). United in the International Biocyclic Vegan Network, members emphasise the closing of organic cycles, systematic humus building and animal ethics, in addition to the classic organic rules (International Biocyclic Vegan Network 2023).

2.2.1 Nutrient management in organic agriculture

In organic agriculture plants should preferably be fed through the soil ecosystem, which means that instead of feeding the plants with soluble “by-passing” nutrients, organic farmers should rather feed the soil, which in turn provides naturally a balanced nutrition for growth (Kirchmann et al. 2008). Organic farmers focus therefore on maintaining and enhancing soil fertility by closing nutrient cycles where possible (IFOAM Organics Europe 2023). The European Union requires that all management practices in organic crop production should be used “to maintain or increase soil organic matter, soil stability and soil biodiversity” (European Union 2018:59). In detail, this means that the fertility and biological activity of soils should be promoted and maintained by:

> (a) multiannual crop rotations with obligatory legumes as the main or cover crop for rotations and other green manure crops;
> (b) the use of short-term green manure crops and legumes and the use of crop diversity, and
> (c) the application of livestock manure or organic material, preferably composted. (European Union 2018:59)

Therefore a well chosen crop mix and rotation, as well as sufficient nutrient recycling through organic fertilizers are the base of organic nutrient management.

Regardless of the type of farm, organic crop rotations can generally be divided into a soil fertility depleting phase and a nourishing phase, according to which the crops are carefully selected, forming a crop mix as a whole (Watson et al. 2002). The nourishing phases are usually supported by three years of clover-grass leys and can be prolonged by a grain legume crop or a short period of nitrogen-fixing green manure (Watson et al. 2002; Goulding et al. 2008). In this way, the nourishing phases form a buffer for the phases in which cash crops are cultivated, as immediately available synthetic fertilisers are not allowed (Watson et al. 2002).

The key for nutrient cycling on organic farms lies in the efficient management of 'wastes' like manure and crop residues (Goulding et al. 2008). In addition to the incorporation of the crop residues left on the fields, livestock has traditionally played an important role in this process. Ruminant livestock has the ability to utilize nutrients from highly cellulosic biomass and thus make them available for human nutrition as well as for agriculture in form of manure (Gerber et al. 2015). However, organic livestock (especially non-ruminants) are also assumed to be mainly dependent on nutrient imports for feed and bedding and are therefore the gateway for conventionally produced inputs into an organic system (Kirchmann et al. 2008). Yet, according to Taramaracz and Clerc (2013) the economic performance of an organic farm depends on manure application. Other common recycling methods include composting and digestion through biogas plants, which do not necessarily require livestock, as biomass can also be simply composted or fermented.

Nutrient management on stockless farms is a challenge, as already mentioned. It is important to note that there are organic stockless farms, which have no or very few animals, but manage by cooperating with other livestock farms or biogas plants for feed and manure or digestate (Schulz et al. 2014). Therefore it is not surprising that Nowak et al. (2013) and Foissy et al. (2013) found that the less livestock a farm has the more organic fertilizer is imported. Of course, a cooperation with a livestock farm is out of the question for biocyclic vegan agriculture. The biocyclic-vegan standard sets therefore a focus on composting (Adolf Hoops Society 2020).

In general, the key concern in organic farming is nutrient availability, compared to conventional nutrient management (Kirchmann et al. 2008). In crop production, high nutrient inputs are required for biomass production in a relatively short period of time and, in particular, for specific growth stages (Kirchmann et al. 2008). However, the availability of nutrients in soil organic matter depends on season and climate, which do not necessarily coincide with growth stages (Kirchmann et al. 2008). Nutrient release from organic fertilisers is also difficult to predict because chemical properties, particle size and distribution, and timing of application can result in mineralisation or immobilisation (Kirchmann et al. 2008).

3. Material & methods

Two farms were modelled representing the nitrogen flow on a stocked and a stockless organic crop farm and compared based on the produced human edible output and the connected emissions. The following sections 3.1 and 3.2 describe the model in further detail including the methods to determine the farm specific parameters and emissions. Additionally the nutritional value was calculated from the produced human edible output, as well as the number of adults that can be fed from it, see section 0. The models were optimized in four scenarios, which is described in section 3.5.

3.1 Farming system model

The farming system model was built on average data of organic cash crop farms in Germany, published in a project report about the assessment of resource efficiency within a German network of pilot farms (Hülsbergen 2022).

In this pilot project, the import of animal manure to organic cash crop farms continues to make these farms dependent on livestock despite their low livestock density. Real farm data from purely stockless organic crop farms are unavailable in the current literature, so the stockless model is a modified version of the stocked farm model based on the pilot project.

Basic properties like the total area, elevation, soil quality, average precipitation and temperature are assumed for both the stocked and the stockless organic farming system (Table 1).

Table 1 Average farm properties for both the stocked and stockless farming system in Germany. Values based on Hülsbergen (2022).

Farm properties	Value	Unit
Total area	237	ha
Elevation	197	hm
Precipitation	757	mm a^{-1}
Average temperature	8,5	°C
Soil quality	56	points

The farm gate was defined as system boundary. In contrast to the classical farm gate nitrogen balance (Van Beek et al. 2003), not only the nitrogen inputs and outputs, but also the nitrogen cycle within the agricultural system was modelled, as vizualized in Figure 2.

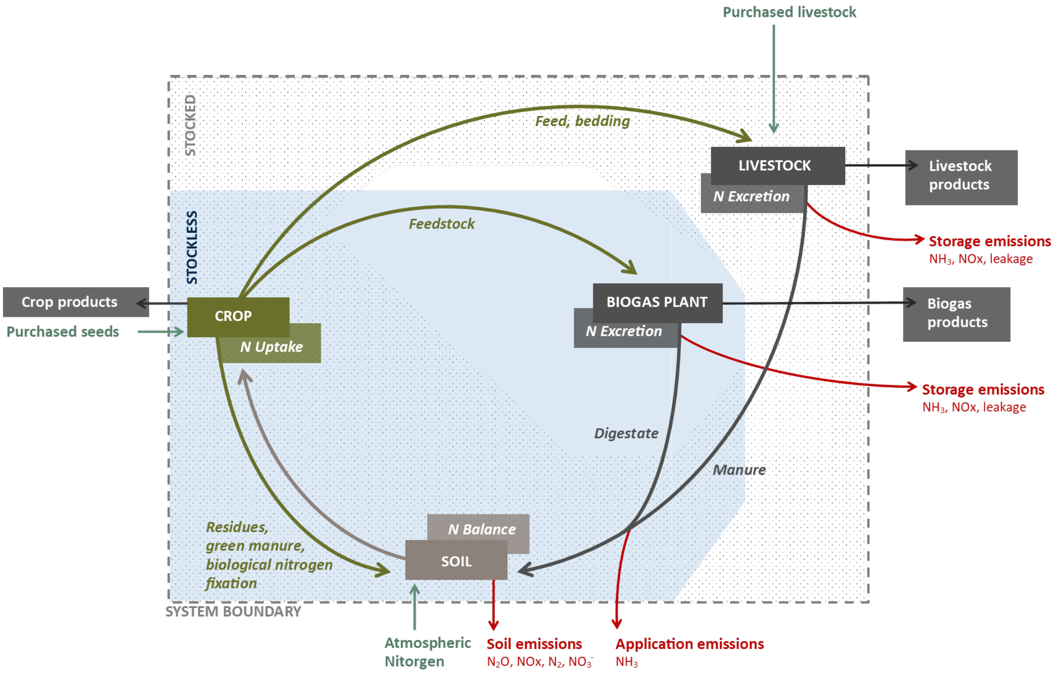

Figure 2 Nitrogen flows in the stocked and stockless organic farming system*. The dotted area visualizes the stocked and the blue area the stockless model. The system boundary is the same for both farming systems and defined as the farm gate.*

The main difference between the two models is the utilization of the feedstock. In case of the stocked system it is digested by livestock, in the stockless system by a biogas plant (Figure 2, dotted and blue area). The excreted nitrogen is in both cases used as fertilizer adding to the nitrogen balance in the soil. While crop production feeds from the soil nitrogen balance for growth, it also returns nutrients in form of harvest residues, green manure, and from biological nitrogen fixing legumes.

The crop output can be either internally used as feedstock or exported for consumption. Products from livestock or biogas production are also leaving the system. The only nitrogen imports assumed are seeds, atmospheric nitrogen deposition, and in the case of the stocked system, young livestock, since for simplicity no on-farm reproduction is assumed. Crop and livestock export were considered as system products for human consumption.

Nitrogen emissions are further described in section 3.2, but mainly occur during storage of manure and digestate, during application of those fertilizers, and from soils. The following subsections outline the methods for the calculations of each farm parameter within the agricultural nitrogen cycle.

The unit for all values was set to kg N ha^{-1} a^{-1}, with the only exception of produced biogas energy which was expressed in thousand (k) MJ ha^{-1} a^{-1}.

3.1.1 Crop production

A crop rotation needs to be adapted to site conditions, the focus of the farm and the knowhow of the farmers, which all vary from farm to farm. Hence, there is no standard crop rotation or crop mix, but only general recommendations. As this study does not consider the effects over time, the focus is only on the crop mix, i.e., the average area share of different crops over time. Good practice in organic farming is a diverse crop mix, balancing intensive crops with less intensive ones, as well as legumes (grain and forage), catch crops, inter crops and green manures (Watson et al. 2002; Kirchmann & Bergström 2008).

Both the stocked and the stockless model were set to a mix, based on the average German organic crop farm by Hülsbergen et al. (2022). The average farming area of this average German organic crop farm was 237 ha (see Table 1). Additionally, Hülsbergen et al. reported an average arable land to grassland proportion of 93:7, which was adopted for this work. Therefore the farming model had 17 ha of grassland and 220 ha of arable land for crop production.

Hülsbergen et al. also reported an average crop mix. Though, the exact types and shares of crops were indicated somewhat ambiguously, as they only had average proportions over all pilot farms, which did not add up, when reported together as a whole. Therefore to build a consistent and realistic crop mix, additional input was assembled from Billen et al. (2021), Jeangros and Courvoisier (2019) as well as from crop rotation guidelines published by the Saxony State Office for Environment, Agriculture and Geology (2022).

Six different crop types were included, as well as catch crops before spring crops and intercrops with tall growing ones. All crops were selected to be typically used for human consumption, with the exception of forage legumes, to meet the main focus of stockless farming, producing only for human consumption. Based on Hülsbergen et al. (2022), winter wheat, potatoes and corn were selected as more intensive crops, with oats as less intensive ones. Here the focus was set on an even mix of grains and tubers. To cover the nitrogen fixing fraction, fava beans were included as grain legume, and alfalfa, and clover grass as forage legume, each to 50%. The forage legumes were assumed to be used to 75% as biogas feedstock or livestock feed (three cuts) and 25% as green manure (fourth cut), to assure nitrogen provision (LfL 2022). The catch and inter crop mix was assumed to consist of only a maximum of 30% legumes to prevent legume fatigue (Jeangros & Courvoisier 2019; LfULG 2022) and planted before potatoes, oats and fava beans, as well as with corn. Catch and cover crops were together with the last cut of forage legumes used as green manure. The proportional share in ha of each crop was set as a variable for model optimization and therefore not defined in advance (see section 3.4).

The nitrogen import through seeds was set for both models to 3 kg N ha^{-1} a^{-1} (Hülsbergen 2022).

Nitrogen yield

Annual nitrogen yields were calculated based on fresh matter yields in decitonnes (dt; 1dt = 100 kg) per ha, published by Hülsbergen et al. (2022). Not all yields were given in Hülsbergen et al. Therefore, where necessary, yield values from organic variety trials conducted by the Bavarian State Research Institute and conventional data, also published by the same institute, were used to fill the gaps. Table 3 summarises all values with the according references.

Nitrogen contents per dt fresh matter were assumed for each crop, either calculated from the crude protein contents of the mentioned organic variety trials of the Bavarian State Institute or, if no organic values were available, taken from the institue's conventional database (for references see Table 2).

Table 2 Yields and Nitrogen yields with references of each crop within the crop mix.

Crop type	**Yield** in dt FM ha^{-1}	**Reference**	**N Yield** in kg N dt FM^{-1}	**Reference**
Oats	35	(Hülsbergen 2022)	1.44	(Urbatzka et al. 2022b)
Winter wheat	39	(Hülsbergen 2022)	1.67	(Urbatzka et al. 2022a)
Winter rye	40	(Hülsbergen 2022)	1.17	(Urbatzka et al. 2022c)
Fava bean	33.7	(Winterling et al. 2022)	1.2	(Winterling et al. 2022)
Potato	278	(Urbatzka et al. 2022d)	0.35*	(LfL 2022)
Corn	123	(Urbatzka 2022)	1.38*	(LfL 2022)
Alfalfa grass	389	(Hülsbergen 2022)	0.58*	(LfL 2022)
Clover grass	357	(Hülsbergen 2022)	0.58*	(LfL 2022)
Grassland	217	(Hülsbergen 2022)	1.82*	(LfL 2022)
Cover crops	150*	(LfL 2022)	0.46*	(LfL 2022)
Intercrops	250*	(LfL 2022)	0.53*	(LfL 2022)

* Conventional values, as no organic yields were available.

The total nitrogen yield per crop was then calculated by multiplying the fresh matter yield by the nitrogen yield per fresh matter and the number of ha the crop was planted (see section 3.4). For comparability, all nitrogen yields per crop were then divided by the total area of land to receive the values in kg N ha^{-1} a^{-1}.

Residues

Residues left after harvest in form of straw above the ground or roots below the ground are important nitrogen source for soil, but also bear risks for emissions.

Above-ground residues can be also used as straw for bedding in livestock production. Below-ground residues were only calculated for evaluation of emissions, see section 3.2.

The Bavarian State Research Institute published ratios for the proportion of yield to above ground residues. The following Table 3 on page 23 summarizes this ratio for crops used in this work as well as the corresponding nitrogen content. The nitrogen content in above ground residues was calculated by multiplying the fresh matter yield of each crop by the corresponding area, the yield to above ground residue ratio and nitrogen content.

The total nitrogen of below ground residues was calculated based on the total nitrogen of above ground residues. The IPCC Guidelines (2019) published a ratio of above ground to below ground residues per crop type, which are also shown in Table 3. To receive the total nitrogen of below ground residues, the total nitrogen of above ground residues was multiplied by the ratio of above ground to below ground residues.

Table 3 Ratio expressing the proportion of yield to above and below ground residues (AG & BG), with corresponding nitrogen contents.

Crop	**Yield:AG residue ratio**	**Nitrogen content AG residues** in kg N dt FM^{-1}	**AG:BG residue ratio**
Oat	1.1	0.5	0.22
Winter wheat	0.8	0.5	0.23
Fava bean	1	1.5	0.29
Potato	0.2	0.2	0.2
Corn	1	0.9	0.22

For further calculations all values for each residue class were summed and divided by the total area, to be expressed in kg N ha^{-1} a^{-1}.

Biological nitrogen fixation

To estimate the total nitrogen input the following formula, conceived by Anglade et al. (2015) was used:

$$Total\ N_{BNF} = \left[\alpha_{cult} * \frac{Y}{NHI} + \beta_{cult}\right] * BGN$$

Total N_{BNF}	*Total nitrogen fixed by legumes in kg N ha^{-1} a^{-1}*
α_{cult}	*Slope coefficient determined by regression analysis, see Anglade et al. (2015)*
β_{cult}	*Intercept coefficient determined by regression*

	analysis, see Anglade et al. (2015)
Y	*Harvested yield per legume in kg N* ha^{-1} a^{-1}
NHI	*Harvest index, ratio of harvested material and above ground production, see Anglade et al. (2015)*
BGN	*Multiplicative factor for below ground contributions, see Anglade et al. (2015)*

Relevant legume crops were selected from the crop mix and together with parameters determined by Anglade et al. (2015) summarized in the following Table 4. Grassland was also included in the calculation as it was assumed to contain up to 20 % of legumes (LfL 2022).

Table 4 Parameters for calculating biological nitrogen fixation.

Crop	α_{cult}	β_{cult}	***NHI***	***BGN***
Alfalfa grass	0.81	-13.9	0.9	1.7
Clover grass	0.78	3.06	0.9	1.7
Fava bean	0.73	5.54	0.74	1.3
Grassland	0.79	-0.49	0.9	1.7

Based on the formula, the parameters and the calculated total nitrogen yield per crop (see previous subsection nitrogen yield), the nitrogen input per crop was determined. To obtain a total nitrogen input by biological nitrogen fixation, all values were summed and divided by the total area. The values were given first in kg N $crop^{-1}$ a^{-1} and then finally in sum as kg N ha^{-1} a^{-1}.

3.1.2 Livestock production

To assure a just comparability, the main focus of the faming systems is crop production. Consequently, the livestock production is assumed to be just a branch of the stocked system and not the the main focus as it would be on a dairy farm. A common form of production is therefore bull fattening. In a wider sense, it can be seen as an extensive counterpart to dairy farming, utilizing calves that are not suitable for breeding and milk production, while maintaining the benefits of ruminant rearing for organic farming.

Livestock was assumed to enter the farming system with a weight of 243kg and leaving the system with a weight of 705kg (Figure 3).

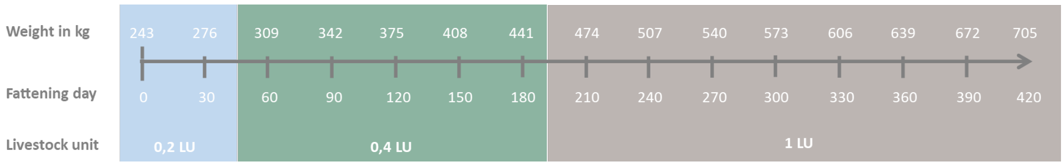

Figure 3 Fattening cycle in organic bull production. *Weights and fattening days were adapted from Piecha (2017), Livestock units (LU) from LfL (2022).*

With an average daily growth of 1100g (Piecha 2017) this cycle would take about 420 days. Assuming a monthly export, the fattening period can be divided into 15 fattening cycles with the same number of animal heads. These must be replaced monthly with calves for the number of bulls exported. The precise number of livestock heads per stage was not defined beforehand since it is an variable for optimization (see section 3.4) and only non-integer numbers of livestock were allowed for simplicity. Nevertheless, the average heads of livestock were calculated by multiplying the fattening stages and heads per stage.

Livestock units (1 LU = 500kg living weight) per ha were calculated by first summing the product of number of heads each stage and the corresponding livestock unit value (LfL 2022), and then dividing the sum by the total area.

Nitrogen import and export of livestock

The number of bulls exported equals the number of bull calves imported, since the farm was assumed to be continuously restocked. Therefore, the imported and exported heads of livestock per year were calculated by multiplying the heads per stage with the number of months per year.

The nitrogen import was calculated by multiplying the number of heads imported or exported with the corresponding live weight and the nitrogen content per live weight. The Bavarian State Research Center for Agriculture published a nitrogen content of 2.7 kg N per dt live weight for beef cattle (LfL 2022).

Nitrogen uptake from feedstock

The nitrogen uptake through feedstock was based on typical dry matter uptakes and feed ration proportions published by the Bavarian State Research Center for Agriculture (LfL 2023). The proportion of roughage to croncentrate was set to 70:30, wich is a somewhat more extensive than suggested in the conventional feeding guidebook (LfL 2023:15) to reflect an organic feeding ration. As forage components, 75% of the alfalfa production and 75% of the clover production as well as the entire grass production was used as roughage. The concentrate share was covered by a proportion of 50:50 oats and corn.

The dry matter intake for bulls >12 months, calves between 6-12 months, and calves <6 months is on average 9.9, 8.3, and 5.8 kg per day and head. Since the nitrogen yield was only given on fresh matter basis, the dry matter feed intake was converted for each age group into dt fresh matter with roughage having 80% fresh matter and both grains having 14% fresh matter (LfL 2022). To obtain the final nitrogen uptake via roughage the fresh matter uptake of each age group was multiplied by the average nitrogen content of alfalfa, clover and grass, the number of heads per age group, and number of days per year. Same has been applied to oat and corn intake. The nitrogen contents were 1.3 kg N dt FM^{-1} in roughage, 1.7 kg N dt FM^{-1} in oats, and 1.38 kg N dt FM^{-1} in corn (LfL 2022). The result values of all age groups were summed per feed component, divided by the total area and therefore given as kg N a^{-1} ha^{-1}.

Bedding

The nitrogen in form of straw used as bedding in livestock production was calculated for each age group of bulls by multiplying the number of heads by the bedding demand and corresponding the nitrogen content. Following demands were assumed based on values published by the Bavarian State Research Institute (LfL 2022), as summarized in Table 2. The nitrogen content of 0.5 kg N dt FM^{-1}, was taken from grains producing straw (winter wheat/ oat), which can be found in the subsection about above ground residues.

Table 5 The demand of straw for bedding in livestock production.

Age group	**Bedding demand** in dt head^{-1} a^{-1}
Bulls >12 months	40.15
Calves 6-12 months	16.06
Calves <6 months	8.03

The total nitrogen contents per age group were then, summed, divided by the total area, and expressed in kg N ha^{-1} a^{-1}.

Nitrogen excretion

Plenty excretion factors for nitrogen excretion in livestock production are available in the literature (IPCC 2019; LfL 2022; Rösemann et al. 2023). But those factors are average default values not connected to the specific feeding rations used in this work. Therefore, the nitrogen excretion was calculated with a mass balance based on model specific parameters going in and out within the livestock production.

$$Total\ Nexc\ = Nupt + Nlimp + Nbed - Nlexp$$

Total Nexc	*Total nitrogen excretion by livestock production in kg N ha*$^{-1}$ *a*$^{-1}$
Nupt	*Total nitrogen uptake through feedstock in livestock production in kg N ha*$^{-1}$ *a*$^{-1}$
Nlimp	*Total nitrogen import through purchased livestock in kg N ha*$^{-1}$ *a*$^{-1}$
Nbed	*Total nitrogen of residues used as bedding in livestock production in kg N ha*$^{-1}$ *a*$^{-1}$
Nlexp	*Total nitrogen export through sold livestock in kg N ha*$^{-1}$ *a*$^{-1}$

3.1.3 Biogas

In the stockless system a biogas plant was included for utilization of the grassland and forage legumes, the latter necessary for maintenance of soil fertility (Watson et al. 2002). Energy crops are directly competing with food production for land (Harvey & Pilgrim 2011; Bartoli et al. 2016; Demartini et al. 2016). To avoid this food – energy crop competition, feedstock was only assumed to consist of non edible crops. Therefore, inspired by Råberg et al. (2018), only forage legumes (alfalfa/clover grass) and grass, all in form of silage, was included as biogas feedstock.

A fraction of nitrogen fed to the biogas plant gets lost in the produced biogas as the raw gas contains some nitrogen mainly in form of NH_3 (Symons & Buswell 1933; Li et al. 2019; Bowman et al. 2022). Those nitrogen losses by removing the produced biogas can amount for about 0-1% of the total nitrogen fed to the biogas (Schievano et al. 2011). In this study these process losses were therefore assumed to be 0.5% which leads to a nitrogen transfer of 99.5% through the biogas plant, which was used to calculate the nitrogen content in the digestate, used as fertilizer for crop production. Thus, the nitrogen excreted was equal to the initial feedstock entering the biogas plant multiplied by the transfer coefficient.

Energy output

The energy yield from biogas production was calculated based on all the grassland production and 75% each of alfalfa grass and clover grass production stored as silage. Average normed gas yields and methane fractions were used from a database, published by the Bavarian State Research Center for Agriculture together with the Bavarian State Ministry of Food, Agriculture and Forestry (StMELF) and summarized in Table 6 on page 28 (LfL & StMELF 2023). Thus, the fresh matter yield in tonnes per ha and year (Table 2 in subsection 3.1.1) was multiplied by the respective gas yield, and the methane fraction. The gas yield was expressed in standard cubic meters (Sm^3) which is the unit for the gas volume under standardized conditions like temperature ($t_s = 0$ °C) and pressure ($P_s = 1.01$ bar) (LfL & StMELF 2023).

Table 6 Average normed gas yields and methane fractions. All crops were assumed to be stored as silage.

Crop	**Normed gas yield** in Sm^3 t FM^{-1}	**Methane fraction**
Alfalfa grass	162	0.55
Clover grass	164	0.55
Grass	174	0.54

Since energy contents of were given in kWh kg^{-1}, the volume of methane first was converted using the ideal gas law and the molar mass of methane. One standard cubic meter of methane has a mass of 0.72 kg, which was multiplied by the volume of methane yield to receive the methane yield in kg ha^{-1} a^{-1}. As a final step, the methane yield was multiplied by the energy content of 13.9 kwh per kg (Nordberg 2023; personal communication), all values were summed and multiplied by 0.001 to obtain the total biogas energy output in MWh ha^{-1} a^{-1}.

3.1.4 Efficiency parameters

In the stocked system two livestock efficiency parameters were calculated. The net livestock production (NLP) stands for the actual livestock growth expressed in nitrogen per ha and year.

$$NLP\ = Nupt + Nbed - TotalNexc$$

NLP	*Net livestock production in kg N ha^{-1} a^{-1}*
Nint	*Total nitrogen intake through feed in livestock production in kg N ha^{-1} a^{-1}*
Nbed	*Total nitrogen of residues used as bedding in livestock production in kg N ha^{-1} a^{-1}*
Total Nexcr.	*Total nitrogen excreted by livestock in kg N ha^{-1} a^{-1}*

As second parameter the body retention rate (BR) was calculated, to reflect the nitrogen use efficiency from livestock production. In order to determine the BR, the NLP is divided by the total nitrogen intake in livestock production (Nint) and multiplied by 100 to obtain the BR in percent.

To evaluate the efficiency of crop production a net crop production (after residues and green manure) was calculated for both models. For this purpose, nitrogen imports through seeds were subtracted from the sum of total nitrogen exported in the form of crop products and total nitrogen used as feedstock.

Finally, to see how much of the nitrogen applied to the soil was actually recycled through the system, a nitrogen recycling rate was calculated. This was calculated by dividing the sum of organic fertiliser (after storage and application emissions), crop residues and green manure by the total nitrogen input to the soil.

3.2 Emissions

Nitrogen emissions occur in various stages and in various forms within the farming system (see Figure 1). Relevant emission sources were identified during storage of feedstock, manure and digestate, during application of fertilizer and when cultivating and using land.

3.2.1 Storage emissions

During storage of organic fertilizer nitrogen emissions in form of ammonia, nitrogen oxides, and nitrous oxide are common, as well as nitrogen losses from leaching and runoff. Losses from storage of feed and biogas feedstock are neglectable, since fodder and energy crops are assumed to be stored as silage (Rösemann et al. 2023). All emissions were calculated with the following formula, but specific emission factors.

$$Nloss_{NH3,\ NOx\ \&\ N2O,\ leach} = EF_{NH3,\ NOx\ \&\ N2O,\ leach}\ *\ Total\ Nexcr.$$

$Nloss_{NH3,\ NOx\ \&\ N2O,\ leach}$	*Total ammonia* (NH_3)*, nitrogen oxides and nitrous oxide* (NOx & N_2O) *emissions as well as total nitrogen losses from leaching and runoff (leach) in kg N* ha^{-1} a^{-1}
$EF_{NH3,\ NOx\ \&\ N2O,\ leach}$	*Emission factor for* (NH_3)*, nitrogen oxides and nigrous oxide* (NOx & N_2O) *emissions as well as total nitrogen losses from leaching and runoff (leak)*
Total Nexcr.	*Total nitrogen excreted by livestock or biogas plant in kg N* ha^{-1} a^{-1}

Ammonia emissions

For both the stocked and the stockless farming system the *Total Nexcr.* equals the nitrogen excreted by livestock and the nitrogen leaving the biogas plant. The emission factor for the stocked farming system is 0.19 (Oenema et al. 2007) and for the stockless farming system 0.0087 (Vos et al. 2022:332).

Nitrous oxide and nitrogen oxide emissions

The emission factor of 0.07 (Oenema et al. 2007) for manure storage in the stocked farming system includes both nitrous oxide and nitrogen oxide emissions. For the stockless farming system the emission factor of 0.000172 for nitrogen oxides and of 0.00172 for nitrous oxide was used, both published by Vos et al. (2022:331). The *Total Nexcr.* follows the assumption made in the previous section on ammonia emissions.

Nitrogen leakage and runoff

Oenema et al. (2007) report also an emission factor of 0.04 for nitrogen losses through leaching and runoff during manure storage.
The *Total Nexcr.* follows the assumption made in the ammonia emissions section.

3.2.2 Application emissions

The application of fertilizer to soil causes ammonia emissions. Those ammonia emissions were calculated according to the following formula, with $Nloss_{NH3}$ standing for the nitrogen contained in ammonia emissions.

$$Nloss_{NH3} = EFappl. * Nappl.$$

$Nloss_{NH3}$	*Total ammonia emissions after fertilizer application in kg N* ha^{-1} a^{-1}
EFappl.	*Emission factor for fertilizer application*
Nappl.	*Total nitrogen applied as fertilizer in kg N* ha^{-1} a^{-1}

In the stocked farming system, the emission factor of 0.19 by Oenema et al. (2007) was used for manure application. The factor refers to total nitrogen excreted, so in the case of the stocked farming system, the *Nappl.* is the total nitrogen excretion before storage losses.
For the application of energy crop derived digestate, within the stockless farming system, the latest, by Vos et al. (2022) reported emission factor of 0.1408 was used. Here refers the factor to the total nitrogen input, therefore the digestate after storage emission was used for the *Nappl.*

3.2.3 Soil emissions

Relevant emissions from managing soil are nitrous oxide, nitrogen oxides, molecular nitrogen and nitrate.

Nitrous oxide

The nitrous oxide emissions are calculated for similar for both the stocked and stockless farming system according to the Tier 1 methodology in the IPCC Guidelines (2019). Since no grazing and drainage, nor organic soils are assumed, the N_2O emissions are calculated as by the following formula, including the nitrogen input through synthetic fertilizer, organic fertilizer, crop residues and atmospheric nitrogen.

$$Nloss_{N2O} = EF_{N2O} * (F_{SN}+F_{ON}+F_{CR}+F_{ATM}+F_{GM})$$

$Nloss_{N2O}$	*Total nitrous oxide emissions from soil management in kg N ha^{-1} a^{-1}*
EF_{N2O}	*Emission factor for managed soil*
F_{SN}	*Applied synthetic fertilizer in kg N ha^{-1} a^{-1}*
F_{ON}	*Applied organic nitrogen in form of livestock manure of biogas digestate in kg N ha^{-1} a^{-1}*
F_{CR}	*Crop residues above and below ground in kg N ha^{-1} a^{-1} minus the nitrogen content of residues used for bedding in livesock production*
F_{ATM}	*Atmospheric nitrogen in kg N ha^{-1} a^{-1}*
F_{GM}	*Green manure in kg N ha^{-1} a^{-1}*

As emission factor was used the aggregated default value of 0.01, which can be found as EF_1 in Table 11.1 of the IPCC report (IPCC 2019:11.12).

Dinitrogen

The emissions of dinitrogen from managed soil were calculated using an assumed ratio of N_2O-N to (N_2O-N+N_2). Scheer et al. (2020) estimates the value of the this ratio for agricultural soils as 0.11. Based on that value, the following formula was used for, dinitrogen emissions in both the stocked and stockless farming system.

$$Nloss_{N2} = (Nloss_{N2O} - 0.1Nloss_{N2O})/0.1$$

$Nloss_{N2}$	*Total dinitrogen emissions from managed soils in kg N ha^{-1} a^{-1}*
$Nloss_{N2O}$	*Total nitrous oxide emissions from managed soils in kg N ha^{-1} a^{-1}*

Nitrogen oxides

The formular for nitrogen oxides emissions was also adapted from the IPCC Guidelines (2019), including the nitrogen input through synthetic fertilizer, organic fertilizer, crop residues and atmospheric nitrogen.

$$Nloss_{NOx} = EF_{NOx} * (F_{SN}+F_{ON}+F_{CR}+F_{ATM}+F_{GM})$$

$Nloss_{NOx}$	*Total nitrogen oxides emissions from soil management in kg N ha^{-1} a^{-1}*
EF_{NOx}	*Emission factor for managed soil*
F_{SN}	*Applied synthetic fertilizer in kg N ha^{-1} a^{-1}*
F_{ON}	*Applied organic nitrogen in form of livestock manure of biogas digestate in kg N ha^{-1} a^{-1}*
F_{CR}	*Crop residues above and below ground in kg N ha^{-1} a^{-1} minus the nitrogen content of residues used for bedding in livesock production*
F_{ATM}	*Atmospheric nitrogen in kg N ha^{-1} a^{-1}*
F_{GM}	*Green manure in kg N ha^{-1} a^{-1}*

For the stocked farming system the emission factor of 0.015 was used, published in Table 8A.1 in the IPCC report (2019:11.39). As suggested by Vos et al. (2022) the emission factor of 0.012 for synthetic fertilizer application was used for calculating the nitrogen oxides emissions within the stockless farming system since no emission factors are available for soil management including biogas digestate.

Nitrate

Nitrate emissions for both the stocked and the stockless farming system are similarly calculated as nitrous oxide and nitrogen oxides emissions, according to the IPCC Guidelines (2019). The following formular also includes the nitrogen input through synthetic fertilizer, organic fertilizer, crop residues and atmospheric nitrogen. The emission factor of 0.24 was taken from Table 11.3 in the IPCC Guidelines (IPCC 2019:11.26).

$$Nloss_{NO3-} = EF_{NO3-} * (F_{SN}+F_{ON}+F_{CR}+F_{ATM}+F_{GM})$$

$Nloss_{NO3-}$	*Total nitrous oxide emissions from soil management in kg N ha^{-1} a^{-1}*
EF_{NO3-}	*Emission factor for managed soil*
F_{SN}	*Applied synthetic fertilizer in kg N ha^{-1} a^{-1}*

F_{ON}	*Applied organic nitrogen in form of livestock manure of biogas digestate in kg N ha*$^{-1}$ *a*$^{-1}$
F_{CR}	*Crop residues above and below ground in kg N ha*$^{-1}$ *a*$^{-1}$ *minus the nitrogen content of residues used for bedding in livesock production*
F_{ATM}	*Atmospheric nitrogen in kg N ha*$^{-1}$ *a*$^{-1}$
F_{GM}	*Green manure in kg N ha*$^{-1}$ *a*$^{-1}$

3.3 Closing the N budget

Nitrogen balances, whether on a soil or farm level, are usually used as sustainability indicator (Küstermann et al. 2010; Lin et al. 2016; Einarsson et al. 2018; Chmelíková et al. 2021; Wivstad et al. 2023). It not only shows whether a farming system manages the nutrient budget sustainably, the difference between in and outputs provides an estimate of nitrogen emissions lost in the system.

In this study all in and outputs, including the nitrogen emissions were calculated. Nitrogen inputs included seeds, above ground residues, biological nitrogen fixation, green manure, and manure and biogas digestate nitrogen (after storage and application losses). Additionally, the atmospheric nitrogen deposition of 6 kg N ha^{-1} a^{-1} was added, adopted from Einarsson et al. (2018).

The nitrogen outputs consisted of two fractions: the nitrogen uptake in crops and nitrogen emissions. The nitrogen uptake included the total nitrogen yield harvested for food, feed, feedstock, or green manure, as well as the total nitrogen from above ground residues. Nitrogen emissions included all gaseous and leaching losses from before and after application of manure or digestate, listed in section 3.2 above.

The balance of both farming systems in this studie's model was consequently calculated by subtracting the sum of nitrogen outputs from nitrogen inputs. But the logical consequence of a nitrogen balance, where all flows were accounted for, is zero. Such a holistic accountance is not suitable as sustainability indicator and not very common. Therefore, this study aimed to close the nitrogen budget or balance at the soil surface level to make the model consistent and did not use the balance as indicator as many other researchers did (Berry et al. 2003; Watson et al. 2006; Nowak et al. 2013; Wivstad et al. 2023). A nitrogen balance of zero is therefore enforced as requirement in the model and its further optimization, see section 3.5. Changes in soil organic matter were generally treated as black box.

3.3.1 Nitrogen surplus and use efficiency

To make the farming system models comparable to other studies, a nitrogen balance, and nitrogen use efficiency was calculated. A nitrogen balance is often declarated as surplus and stands for the difference between inputs and outputs of a system. There are several levels where this surplus can be calculated in a farming system, depending on the defined system boundary. As mentioned, setting the system boundaries for this model to the soil surface, the surplus would result even, as all in and outputs, including emissions were already calculated (see section 3.3). Therefore, the nitrogen surplus was only calculated at the farm gate level by building up the difference between all nitrogen imports to the farm (seed and livestock import, atmospheric nitrogen, biological nitrogen fixation) and all nitrogen exports from the farm (crop and livestock export). The surplus had the unit kg N ha^{-1} a^{-1}.

The nitrogen use efficiency was calculated at the soil surface level, to validate the estimated nitrogen flows within the farming system. For this purpose, the sum of all nitrogen removed from the soil (raw materials, crop residues, green manure, exported crops) was divided by the total nitrogen input to the soil (manure/digestate before emissions, atmospheric nitrogen, biological nitrogen fixation, seed import, green manure, crop residues). The values were expressed in percentage of the total nitrogen input.

3.4 Nutritional value

The nutritional value was determined by calculating the crude protein, energy, and fat content of the produced human edible output. All calculations were based on the values of exported livestock and/or crop products.

3.4.1 Crude protein content

The crude protein for grains was calculated by using the nitrogen yield per ha and year of every exported grain and multiply with nitrogen to protein conversion factors published by Mariotti et al. (2008). To determine the total crude protein output from crop production, all crude protein contents from grains of one scenario were summed and divided by the total area.

In case of the stocked system the total weight of exported bulls needed to be converted to empty body weight with a conversion factor of 0.93, to enable the determination of edible share of muscle and fat tissue (Honig et al. 2022). All muscle and fat were assumed to be usable for human consumption, so the proportions suggested by Honig et al. of 42.7% for muscle and 16.4% for fat tissue were multiplied by the calculated empty body weight. For both tissues the protein content was calculated according to Honig et al. (2022). To receive the total crude protein production per scenario the crude protein output from livestock was divided by the total farming area. For a total crude protein production per scenario the protein content from livestock was added to the produced protein content from crop production. All crude protein values, expressed in kg CP ha^{-1} a^{-1},were reported seperatedly per origin and as a total per scenario.

3.4.2 Energy content

Energy contents for all grains were calculated by multiplying the (metabolizable) energy contents, published by the Bavarian State Research Center for Agriculture, with the yield of each grain type (LfL 2021).

The energy content of livestock products was calculated similarly to crude protein content, based on Honig et al.(2022). The edible share of muscle and fat tissue was multiplied with the respective energy content.

All energy contents were added per scenario and expressed in gigajoule (GJ; 1 MJ = 1000 GJ) ha^{-1} a^{-1}.

3.4.3 Fat content

Fat contents for grains and other vegetal products published by the U.S. Department of Agriculture (USDA 2023) and the Norwegian Food Safety Authority (NFSA 2022) were multiplied by the yield of each grain type. To determine the total fat output from crop production, all fat contents from grains of one scenario were summed and divided by the total area.

For the total fat output from livestock production, the share of fat tissue per exported bull was calculated as suggested in 3.3.1 according to Honig et al. (2022). The fat from livestock production was also divided by the total area to be reported seperatedly and additionally summed with the fat content of grains produced in the same scenario to also have a total fat output for the stocked system.

All fat contents were expressed in kg fat ha^{-1} a^{-1}.

3.4.4 Supported population

The supported population stands for how many people can be fed from the crude protein, energy, and fat output, of each optimization scenario (see 3.4). An average crude protein, energy and fat intake of adults was determined assuming an average body weight of 70kg (Walpole et al. 2012) with an active, moderately active lifestyle and an average age of 57 years (Eurostat 2023).

The World Health Organization recommends a crude protein intake of 0.66 g per kg body weight per day (WHO et al. 2007). Multiplied by the average body weight and days per year gives a total crude protein intake of 16.9 kg per adult and year.

The energy demand is dependent on body weight, gender, age, and level of activity (FAO et al. 2004). To ensure gender equality the average energy demand was based on values of a 57 year old woman and man, both with a weight of 70kg and an active, moderately active lifestyle. The default value was therefore the calculated average of FAO values for both gender and accounts 995000 kcal or 4.2 GJ per person and year (FAO et al. 2004).

The most recent WHO recommendation for fat intake in adult nutrition is <30% of the total energy intake (WHO 2023). Therefore, 298388 kcal of the total 994625 kcal per year should be covered by fat. Assuming an energy content of 8.98 kcal per gram fat (Rolls 2000), the maximum amount of fat intake was calculated to be 33261 g or 33.3 kg fat per year.

To obtain the supported population, the crude protein, energy and fat output was devided by the default intake value of each nutritional value. Results were expressed in adults ha^{-1} a^{-1}.

3.5 Model optimization

Each model was optimized according to four scenarios. One to receive an optimal the nitrogen cycle with an even nitrogen budget and the other three to receive maximum crude protein, energy, and fat output for human consumption. The area of each crop and additionally, in case of the stocked system, livestock heads were adjusted to achieve a closed nitrogen budget (see section 3.3) while maximizing total edible output for humans. The whole optimization was run on the nonlinear solver function in Microsoft Excel. The program optimizes a defined objective cell by changing the values of defined variable cells while fulfilling given mathematical constraints which can be equalities or inequalities. Consequently, the nutritional output per scenario was defined as the objective cell. In the stocked scenarios, livestock heads and area per crop were defined as variable cells, while in the stockless scenarios, the variables were only crop area. The area for grassland (17 ha) was not set as variable to see possible differences grassland utilization.

3.5.1 Optimization constraints

Next to objective and variable cells, constraints needed to be defined to reflect the real world farming logic in this mathematical optimization. As general property, and as defined in section 3.1 Table 1 the total farming area was set to 237 ha and as mentioned in section 3.1.1, the soil budget was set even for model consistancy (see section 3.3).

$$\begin{array}{lcl} \textit{Total ha} & = & \textit{237 ha} \\ \textit{Soil budget} & = & \textit{0} \end{array}$$

Same constraints were given for both models, including their scenarios, in crop production. For better management, each area per crop was divided by the total

arable area. In this way, the share of crops in the total arable land could be expressed in fractions. To ensure a realistic crop mix, each major crop (**O**at, **w**inter **W**heat, **P**otato, **C**orn) was set to a minimum proportion of 10%, which means that each major crop had to be cultivated on at least 10% of the total arable land. At the same time a upper limit of 1/3 was set for total cereals (O & wW), and corn and potato, to reach the suggested even distribution of froage, root and cereal crops (LfULG 2022).
To avoid soil-borne diseases and pests in potato production, Jeangros and Couvoisier (2019) recommend a maximum percentage of 25% in the crop mix.

Share of O/wW/P/C >= 0.1
Share of cereals < = 0.33
Share of corn and potatoes < = 0.33
Share of potatoes <= 0.25

Similar applies to legumes. Guidelines of the Saxony State Office for Environment, Agriculture and Geology indicate a maximum productivity of legumes in the crop mix with a total share of 35% (LfULG 2022), which was therefore set as maximum limit for cultivation of all legume types. All legumes were set to a minimum cultivation of 5% of the total arable land (minimum limit), out of the reason that all legume types were included in the crop mix. The Saxony State Office also recommended additionally a maximum share of alfalfa of 20% in the crop mix to prevent legume fatigue (LfULG 2022).

Maximum limit of legumes < = 0.35
Minimum limit of legumes >= 0.05
Alfalfa grass share <= 0.2

In case of the stocked system additional constraints were necessary to ensure a realistic livestock production. The focus was on linking the feedstock provision by crop production with the actual uptake by livestock. Since livestock is the only roughage utilizer in this system, the intake of production was set equal.

Roughage uptake = Roughage produced
Oat intake < = Oat produced
Corn intake < = Corn produced

In contrast, more oats and corn should be possible to be produced than the livestock utilized, since both grains are also used in human nutrition. In general, land that was not occupied by a crop as a result of optimization was considered fallow.

3.5.2 Sensitivity analysis

A sensitivity analysis was conducted to test the influence of specific assumptions and constraints on the optimization outcome. The first test was to check the influence of feed components in the livestock feed ration on food production. The current feed ration was built based on the assumption that grains can be fed to livestock as, they convert it to food. From a feed versus food competition perspective this can be questioned, see assumptions for biogas feedstock, section 3.1.3. The stocked scenarios were therefore additionally run on a feed ration excluding oat and corn as feed.

As a second test, the upper constraints of the legume, cereal, and potato & corn share was removed to see how the crop mix is limited and how these constraints would affect the food productivity.

4. Results

The results were approached from the perspective of an optimized nitrogen cycle and from the perspective of optimized nutritional values. It should be noted that in the crop mix the distribution of the 220 ha of arable land among the respective crops was variable, whereas the grassland share of 17 ha remains constant in all scenarios.

4.1 Nitrogen cycle

Considering the nitrogen cycle, there were slight differences in how the stocked and stockless farming systems reached a comparable net nitrogen export (equals net food production). Both systems exported about 60 kg N ha^{-1} a^{-1} (difference of 3 kg N ha^{-1} a^{-1}), but the distribution of arable land within the crop mix varied (Figure 4). Therefore after optimization, the major crops cultivated differed. The stockless farming system had a smaller share of legumes in the crop mix and relied mainly on winter wheat and potato as major crops. The farming system with livestock relied on winter wheat and corn, and was was able to support 0.46 LU ha^{-1} with its crop mix, which equals about 122 heads of bulls exported per year.

The Sankey diagrams on the following page 39 visualize the entire nitrogen flows of each farming system (Figure 5 & 6). The total nitrogen input (all nitrogen inputs to soil, before losses) amounts about 301 kg N ha^{-1} a^{-1} in the stocked system, nevertheless about 14% was lost during storage and application, and 15% due to soil management. About 90% of the total emissions were reactive nitrogen. As mentioned, the stocked farming system produced 57.4 kg N ha^{-1} a^{-1} (net food production) in form of crop

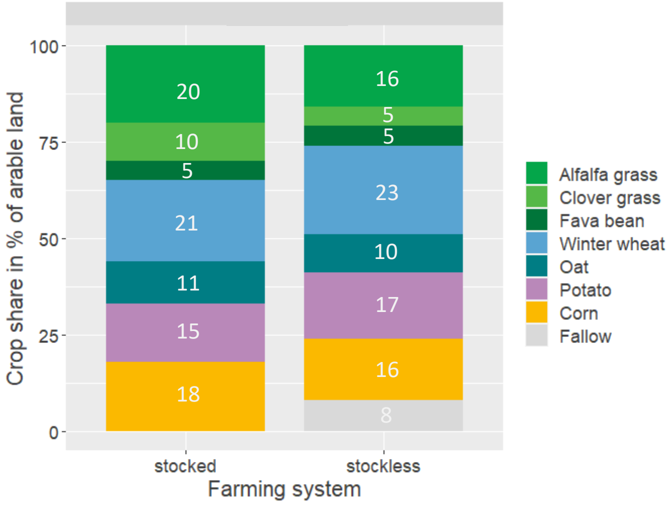

Figure 4 Crop mix according to nitrogen optimizaiton in the stocked and the stockless system*. Values are given as percentage of the total arable land of 220 ha.*

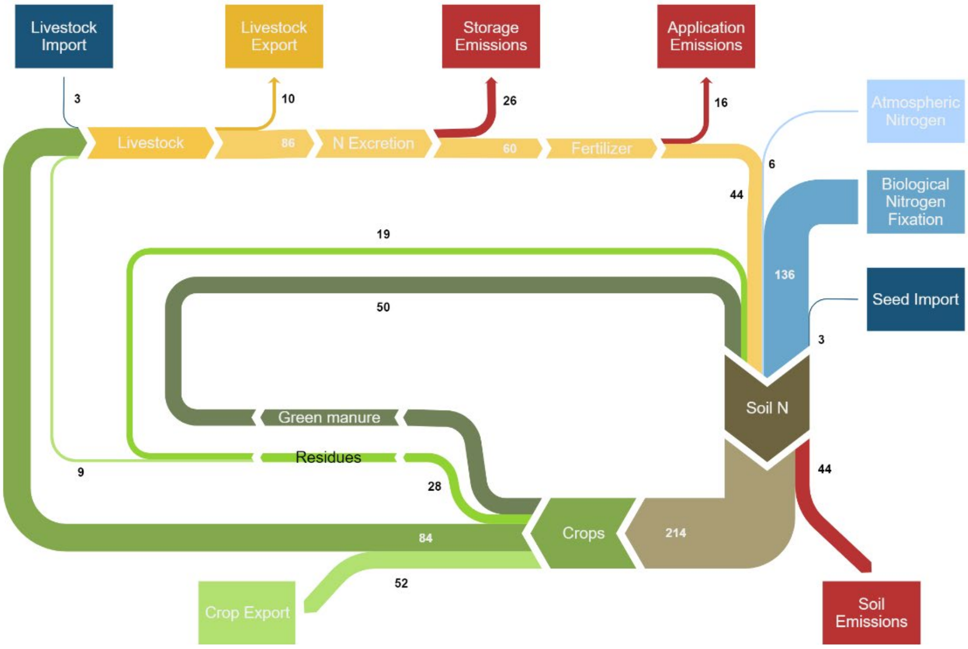

Figure 5 Nitrogen flows on the stocked farming system. *The on farm nitrogen cycle is closed by livestock, utilizing crops and producing manure, as well as harvest residues and green manure returned to soil. Legume cultivation is the main source of nitrogen through biological nitrogen fixation. Nitrogen is leaving the system either as food (livestock or crop) or emissions. All values are given in kg N* ha^{-1} a^{-1}.

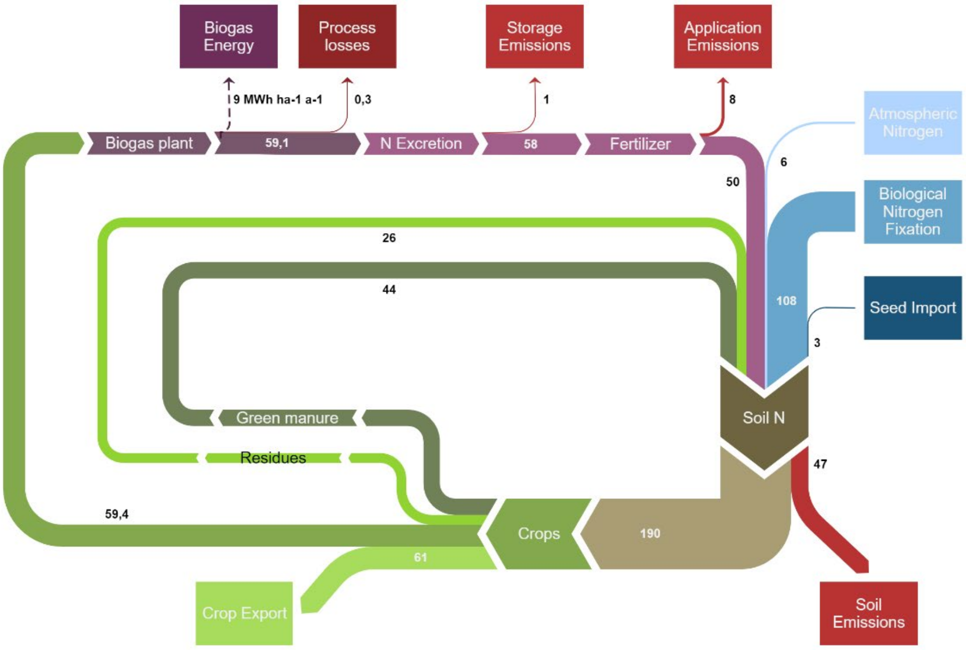

Figure 6 Nitrogen flows on the stockless farming system. *The on farm nitrogen cycle is closed by a biogas plant, utilizing crops and producing digestate, as well as harvest residues and green manure returned to soil. Legume cultivation is the main source of nitrogen through biological nitrogen fixation. Nitrogen is leaving the system either as food (crops) or emissions. All values are given in kg N* ha^{-1} a^{-1}.

and livestock products, exported for human consumption. The export accounts for about 19% of the total nitrogen input, with only 2% produced by livestock production (net livestock production 7 kg N ha^{-1} a^{-1}). But Figure 5 also shows that feed production was the largest single nitrogen consumer of total nitrogen input at 84 kg N ha^{-1} a^{-1} (28%), where 52% of the nitrogen in feed was returned to the field. About 38% of the total nitrogen input was recycled in form of green manure (51 kg N ha^{-1} a^{-1}), livestock manure (44 kg N ha^{-1} a^{-1}) and harvest residues (19 kg N ha^{-1} a^{-1}). However, biological nitrogen fixation accounted for the largest share of nitrogen input to soil at 136 kg N ha^{-1} a^{-1} (45%). Of the total nitrogen input, 68% was utilized in crop production (crop export, feedstock, crop residues, green manure). The stocked farming system had a nitrogen surplus of 87 kg N ha^{-1} a^{-1} on the farm gate level.

The total nitrogen input (all nitrogen inputs to soil, before losses) in the stockless farming system was at 246 kg N ha^{-1} a^{-1}, where just about 0.1% were lost within the biogas plant (transition or process losses). Additional 4% were emitted during digestate storage and application, as well as 19% due to soil management. In total about 56 kg N ha^{-1} a^{-1} was lost during production and by further digestate management, of which 44 kg N ha^{-1} a^{-1} was reactive nitrogen. Figure 6 indicates that about 24% of the total N input, the mentioned 60 kg N ha^{-1} a^{-1}, was exported for human consumption (net food production), whereas 24% of the total nitrogen went into biogas production as feedstock (54 kg N ha^{-1} a^{-1}). About 85% of the nitrogen in feedstock was returned to the field. Via digestate (59 kg N ha^{-1} a^{-1}), green manure (44 kg N ha^{-1} a^{-1}) and harvest residues (26 kg N ha^{-1} a^{-1}) about 52% of the total nitrogen input was returned to the soil. Thus, biological nitrogen fixation provided with 108 kg N ha^{-1} a^{-1} the largest nitrogen inflow to the soil, which amounts about 44% of the total nitrogen input. About 77% of the total nitrogen input was utilized in crop production. On a farm gate level, the stockless farming system had a surplus of 56 kg N ha^{-1} a^{-1}.

4.2 Nutritional value

The quantity of nutritional value generated by each optimization scenario, and more importantly, the number of people that can be fed per year as a result, has been summarized in Table 8, page 41.

With the optimization for nitrogen (nitrogen cycle in previous section 4.1), both farming systems were able to export a total of 61 kg N ha^{-1} a^{-1} for human consumption. But in terms of crude protein, energy and fat, the stockless farm supplied the same or even more people with crude protein and energy compared to the stocked farm, which was the opposite in terms of fat supply. When optimizing for a macronutrient output other than nitrogen, nitrogen flows varied within both

Table 7 Nutritional results when optimising the stocked and stockless system for nitrogen, crude protein, energy and fat output.

		Stocked farming system				**Stockless farming system**				**Unit**
	Optimized for	*Nitrogen*	*Crude protein*	*Energy*	*Fat*	*Nitrogen*	*Crude protein*	*Energy*	*Fat*	
Nutritional value	Total N	**61**	61	58	61	**61**	61	60	59	kg N ha^{-1} a^{-1}
	Total CP	303	**305**	276	303	320	**326**	308	300	kg CP ha^{-1} a^{-1}
	CP plant	270	271	245	270	320	326	308	300	kg CP ha^{-1} a^{-1}
	CP livestock	34	34	31	34	-	-	**-**	-	kg CP ha^{-1} a^{-1}
	Total GJ	84	81	**97**	84	92	79	**103**	101	GJ ha^{-1} a^{-1}
	Total fat	251	246	247	**251**	219	212	219	**235**	kg fat ha^{-1} a^{-1}
	Fat plant	196	191	197	196	219	212	219	235	kg fat ha^{-1} a^{-1}
	Fat livestock	55	55	50	55	-	-	-	-	kg fat ha^{-1} a^{-1}
Supported population	Crude Protein	18	18	16	18	18	19	18	18	Adults ha^{-1}
	CP plant	16	16	14	16	18	19	18	18	Adults ha^{-1}
	CP livestock	2	2	2	2	-	-	-	-	Adults ha^{-1}
	Energy	20	19	23	20	22	19	25	24	Adults ha^{-1}
	Fat	8	8	8	8	7	6	7	7	Adults ha^{-1}
	Fat plant	6	6	6	6	7	6	7	7	Adults ha^{-1}
	Fat livestock	2	2	2	2	-	-	-	-	Adults ha^{-1}

Table 8 On farm nitrogen flows when optimizing the stocked and stockless organic farming system for crude protein, energy and fat output.

		Stocked farming system						**Stockless farming system**						**Unit**
	Optimized for	*Crude protein*		*Energy*		*Fat*		*Crude protein*		*Energy*		*Fat*		*Share of total N input in %*
Productivity	Total N input	301		272		301		263		239		237		kg N ha^{-1} a^{-1}
	Crop export	52		49		52		61		60		59		kg N ha^{-1} a^{-1}
	Livestock export	10		9		10		-		-		-		kg N ha^{-1} a^{-1}
	Net food production	57	*19%*	54	*20%*	57	*19%*	59	*23%*	59	*25%*	57	*24%*	kg N ha^{-1} a^{-1}
	Energy export	-		-		-		9.3		8.4		8.3		Mwh ha^{-1} a^{-1}
Livestock & Biogas	Feedstock	84	*28%*	77	*28%*	84	*28%*	62	*23%*	56	*23%*	55	*23%*	kg N ha^{-1} a^{-1}
	Manure/digestate	86		84		86		62		56		55		kg N ha^{-1} a^{-1}
	Effective fertilizer	44		43		44		52		47		47		kg N ha^{-1} a^{-1}
Soil & Crops	BNF	136	*45%*	126	*46%*	136	*45%*	112	*43%*	105	*44%*	103	*44%*	kg N ha^{-1} a^{-1}
	Harvest residues	19	*6%*	8	*3%*	19	*6%*	31	*12%*	24	*10%*	25	*10%*	kg N ha^{-1} a^{-1}
	Green manure	50	*17%*	46	*17%*	51	*17%*	49	*19%*	45	*19%*	45	*19%*	kg N ha^{-1} a^{-1}
Efficiency parameter	N Surplus (farm gate)	87		80		87		61		54		54		kg N ha^{-1} a^{-1}
	NUE (soil surface)		*68%*		*66%*		*68%*		*77%*		*78%*		*77%*	
	N recycling rate		*38%*		*36%*		*38%*		*50%*		*49%*		*49%*	

Table 9 On farm nitrogen emissions when optimizing the stocked and stockless organic farming system for crude protein, energy and fat output.

		Stocked farming system						**Stockless farming system**						**Unit**
	Optimized for	*Crude protein*		*Energy*		*Fat*		*Crude protein*		*Energy*		*Fat*		*Share of total N input in %*
Emissions	Transition	-		-		-		0.3	*0.1%*	0.3	*0.1%*	0.3	*0.1%*	kg N ha^{-1} a^{-1}
	Storage	26	*9%*	25	*9%*	26	*9%*	1	*0.2%*	1	*0.2%*	1	*0.2%*	kg N ha^{-1} a^{-1}
	Application	16	*5%*	16	*6%*	16	*5%*	9	*3%*	8	*3%*	8	*3%*	kg N ha^{-1} a^{-1}
	Soil	44	*15%*	38	*14%*	44	*15%*	51	*19%*	45	*19%*	45	*19%*	kg N ha^{-1} a^{-1}
	Total	87		79		87		61		54		54		kg N ha^{-1} a^{-1}
	Reactive nitrogen	75		70		75		48		42		42		kg N ha^{-1} a^{-1}

models and between the scenarios as can be taken from Table 9 and 10 which can be found on the previous pages (page 42 – 44).

An optimization of crude protein resulted in a maximum crude protein supply of 305 kg CP ha^{-1} a^{-1} in the stocked model and 326 kg CP ha^{-1} a^{-1} in the stockless one. To reach the maximum crude protein production in the stocked model the crop mix shifted slightly towards more winter wheat and corn cultivation but did not change markedly (see Appenix 1, Figure 7). The livestock production (0.46 LU ha^{-1} a^{-1}), total nitrogen input (301 kg N ha^{-1} a^{-1}) and net food productivity (57 kg N ha^{-1} a^{-1}) stayed at the level of the basic optimization for nitrogen. For maximum output of crude protein in the stockless system, the crop mix shifted towards more corn production. The stockless crude protein scenarios was able to supply a larger population in terms of crude protein. Both systems provided the same amount of dietary energy, however, when the fat supply of these scenarios was considered in addition, the stocked farming system was able to support a larger population.

The maximum food energy supply was reached at 97 GJ ha^{-1} a^{-1} in the stocked and at 103 GJ ha^{-1} a^{-1} in the stockless model. The total nitrogen input and net food production was with 272 kg N ha^{-1} a^{-1} and 54 kg N ha^{-1} a^{-1} in the stocked energy scenario low compared to the other stocked optimization scenarios. It was also the optimization with the lowest livestock units per hectar (0.42 LU ha^{-1} a^{-1}) and lowest nitrogen use efficiency (66%), yet the net food productivity in relation to the total nitrogen input was with 20% the highest within the stocked optimization scenarios. The stockless optimization for energy resulted in the same net food production as the stockless crude protein optimization (59 kg N ha^{-1} a^{-1}), but the net productivity in relation to the total nitrogen input was with 25% higher in the energy scenario (see Table 8). The crop mix consisted in both, the stocked and the stockless energy scenario mainly of winter wheat and corn (see Appenix 1, Figure 7). The stockless energy scenario was able to support a larger population for energy and crude protein, whereas the stocked scenario supplied more adults with fat.

Maximising the fat supply in the stocked and the stockless model resulted in 251 kg fat ha^{-1} a^{-1} and 235 kg fat ha^{-1} a^{-1}. The stocked scenario for fat optimization turned out to have the same total nitrogen input, net food production and crop mix as the optimization for nitrogen. The stockless optimization for fat had compared to the other stockless optimizations the lowest total nitrogen input (237 kg N ha^{-1} a^{-1}) and net food production (57 kg N ha^{-1} a^{-1}). The main crops were oat and potato (see Appenix 1, Figure 7). The stocked system supplied, apart from energy, the same and a larger population with crude protein and fat.

On average produced the system without livestock more crude protein and energy, while the system with livestock had higher fat production on average.This was also seen in the number of supported population. In terms of crude protein production, both systems were roughly on par with supply. However, the stockless model was able to supply on average 2 more adults per ha with energy, while in the stocked model about the opposite applied for fat supply. In all optimizations was fat the macronutrient with the least adults supported.

Overall managed the stockless system a higher nitrogen recycling rate, compared to the stocked scenarios, which could be also seen in the amount of effective fertilizer. The proportions of biological nitrogen fixation, nitrogen recycling, or emissions, deviated in general only for a maximum of 2% within a model (Table 9). The total emissions and reactive nitrogen emissions were lower in the stockless scenarios, but had in general higher emissions during soil management compared to the stocked scenarios (Table 10). All stockless scenarios produced additional 8 to 9 MWh per ha^{-1} a^{-1} of non dietary energy due to biogas production. The rate of nitrogen body retention with regard to nitrogen was in all four stocked scenarios at 8%. The efficiency of nitrogen use in crop production was in the stocked scenarios on average lower than in the stockless.

4.3 Sensitivity analysis

In the first test, when restricting livestock feedstock to roughage just from forage legumes and grassland the livestock density dropped from 0.46 to 0.32. Crop mix shifted from corn and oat production to more winter wheat and potato. The population supported changed only marginally (see Appendix 2, Table 11), but more individuals were supported with protein, slightly outperforming even the stockless basic scenarios. Energy production stayed the same and fat production decreased, getting on the same level of the stockless system.

By opening the upper constraints for the crop mix in test two, the area proportions in the stocked scenarios shifted towards more (forage) legumes and corn & potatoes cultivation, while cereals fell below the 1/3 limit set in the original optimization. In the stockless scenarios the crop mix concentrated on corn & potato production, whereas both, legumes and grains dropped below the 1/3 limit. Livestock production went up from 0.46 to 0.51. These changes resulted in higher nitrogen fluxes and overall food production (Appendix 2, Table 12), but the relations between the scenarios in terms of supported population remained the same. However, on average, the difference in supported population from the original optimisation varied by only 1 individual on average.

5. Discussion

The essence of this work was to challenge the common assumption of organic agricultural systems being dependent on livestock. Although the majority of studies have been questioning the sufficiency of stockless organic farms from a nutrient management perspective (Goulding et al. 2008; Borgen et al. 2012; Foissy et al. 2013; Ball et al. 2018), to my knowledge, this particular hypothesis has never been approached holistically from a nutrient management perspective including the value produced for human nutrition. Therefore, at a time when livestock production must be reduced while sustainable agricultural systems need to be expanded, this work contributes to the broader discussion of whether livestock production is critical to a sustainable future food system.

To place this thesis in the current body of literature, the nitrogen surplus and nitrogen use efficiency, calculated in this study, can be used as a basis for comparison to other farming system models and calculations. In both farming systems, the farm-gate nitrogen surplus (average of all scenarios: stocked 85 kg N ha^{-1} a^{-1}, stockless 77 kg N ha^{-1} a^{-1}) was close to or lower than the German average farm surplus (87 kg N ha^{-1} a^{-1}) published as a 5-year average by the German Federal Environmental Agency (Umwelt Bundesamt, UBA 2023). Thus from an environmental perspective, the stocked and the stockless farming system were above the recommended surplus of 0-50 kg N ha^{-1} a^{-1} (Hülsbergen 2003; Christen et al. 2009). The numbers fit in well with the nitrogen surpluses for organic farms estimated in Einarsson et al. (2018), Hülsbergen et al. (2022) and Wivstad et al. (2023), thus most were for dairy farms. Nevertheless, the results of Hülsbergen et al. (2022) confirmed the tendency that organic crop-oriented farms generally have a lower nitrogen surplus than organic farms with livestock, which can be in this case explained by the additional nitrogen imports through livestock.

The nitrogen efficiency values out there are rather confusing, as there is no standardized definition of this indicator and the system boundaries vary from the soil surface to the farm gate or even to the whole chain level (Lin et al. 2016; Einarsson et al. 2018; Wivstad et al. 2023). Nitrogen use efficiency was defined in this thesis as the ratio of output to input from the soil, as the on-farm nitrogen flows were of interest. Chmelíková et al. (2021) published a general range for organic farms (stocked and stockless) of 61-121% on a soil surface level. Both the stocked (68%)

and the stockless model (73%) were in this range, but at the lower end. When considering only farms with livestock at the soil surface level, nitrogen use efficiencies range from 26% (Wivstad et al. 2023) to 95% (Chmelíková et al. 2021). With such a wide span, the stocked system model with 68% is well in the midrange, but the structures of stocked farms are diverse. Stocked farms can be dairy farms, as the ones from the mentioned minimum and maximum value, but also organic arable farms with different livestock densities from zero (Chmelíková et al. 2021) to up to 1.4 livestock units per ha (Küstermann et al. 2010). Even if there is no livestock, farms usually still import to a large extend animal derived fertilizers (Nowak et al. 2013; Chmelíková et al. 2021). So where is the line to draw between a stocked and stockless farming system? With the definition used in this work a stockless system would be strictly without any animal input, thus to my knowledge such a farming system has so far never been investigated. The differences are not only in livestock densities, but also in the corresponding crop mixes. Dairy farms have usually a much higher grassland and (green) fodder production than farms with a main focus on grains (Chmelíková et al. 2021; Wivstad et al. 2023), which may impact the in and outputs and therefore also the nitrogen use efficiency. As with the stockless system no comparable modelled farm with beef production was found for the stocked farming system in this work. Comparisons of different studies based on nitrogen efficiency should be made with caution, but the ranges show that the nitrogen use efficiencies achieved in this work are within a realistic margin.

5.1 The role of livestock in nitrogen circulation

Four questions can be used to analyze the role of livestock in the nitrogen cycle. The first is (i) how much contributes livestock to total soil nitrogen inputs? The fluxes to the soil in Figure 4 clearly show that the main nitrogen input in the stocked model was not livestock derived fertilizer, but biological nitrogen fixation by legumes. The same could be observed for the stockless model with digestate, which was to be expected in both cases. Bilogical nitrogen fixation as major nitrogen provider in organic agricultural systems is a recurring and generally accepted finding in research (Goulding et al. 2008; Lin et al. 2016; Einarsson et al. 2018), especially on farms with no fertilizer import (Nowak et al. 2013). Compared to manure, digestate, green manure, or crop residues, biologically fixed nitrogen is an external nitrogen input to the farm and has not yet been part of the on-farm nitrogen cycle, unlike the soil inputs just mentioned. When summing all those soil inputs that have been recirculated (stocked 113 kg N ha^{-1} a^{-1}, stockless 120 kg N ha^{-1} a^{-1}), it becomes clear that the stocked system relied more on external nitrogen inputs, than the stockless one. Effectively, manure from livestock contributed only 15% of the total nitrogen inputs, biogas digestate 20%. These proportions could change with higher livestock densities or higher biogas production, but this might also result in dependence on imports and thus loss of self-sufficiency. However, regardless of the origin, the sole nitrogen input to the soil from organic fertilizers was not the primary nitrogen provider in either system.

Second, it needs to be identified (ii) how livestock contribute to nutrient recycling on the farm. The overall nitrogen recycling rate, including nitrogen delivered by green manure, livestock manure or digestate, and harvest residues, as a percentage of the total nitrogen input to the soil, was slightly lower on the stocked farm (38%) than on the stockless farm (49%). In both systems, the recycling pathway via feedstock to livestock or biogas was the largest outflow from the soil. However, the recycling product returned, in form of livestock manure in the stocked farming system, was only the second largest of all recycling streams, in contrast to the stockless system using the biogas plant. Recycling by livestock or biogas plants can be seen in two phases: the actual recycling process by digestion, and everything that happens after the livestock manure or digestate is excreted or produced.
In the stocked model, livestock convert 8% of the nitrogen they ingest from feedstock into body mass. Conversely, 92% of the nitrogen in the diet must have left the body in the form of manure (including urine) (Oenema et al. 2001). Šebek et al. (2012:50) published a nitrogen body retention of 9.7 for German fattening bulls, which is slightly higher than in this thesis, thus they also used a lower starting weight. For biogas production, the nutrient transfer coefficient almost at 100% (Schievano et al. 2011) and is therefore one of the most effective compared to other non-animal recycling methods. During composting for example, 88% of the nitrogen going in is already lost as emissions during the decomposition process (Tiquia et al. 2002; Goulding et al. 2008; Wong et al. 2017). Changing the recycling system in the stockless model to composting, could therefore result in an even lower recycling rate in the stockless system and thus generally change the ratios and ranking of the flows contributing to the total nitrogen input addressed in (i). So it really depends on what the stocked system is being compared to.

But as mentioned, the recycling process itself is not the end of the recycling pathway, leading also to the third question: (iii) What are the relative emissions of each model? Although livestock may be almost as efficient as the biogas plant during the actual recycling process, the downstream stages, storage, application, and land management turn the (recycling) efficiency ratio around. The emissions especially during storage and application depend highly on the handling and management system of the organic feritlizer, adding quite an uncertainty to emission estimations (Oenema et al. 2007; Möller 2015; Vos et al. 2022; Pedersen & Hafner 2023). About 30% of the manure excreted in the livestock model was lost during storage and 19% during application, which means that only 51% of the excreted manure was recovered and applied as plant nutrient, which is very close to the results of

Oenema et al. (2007). During the storage and application of biogas digestate, only 16% of the nitrogen in the digestate produced was lost in total, which is significantly less than nitrogen losses during storage and application of livestock manure.

This may be due to differences in storage technology and physical properties of the digestate when applying, but also to the fact that emission factors for losses during biogas production and handling is not yet fully researched (Möller 2015; Vos et al. 2022; Pedersen & Hafner 2023). Pedersen & Hafner (2023) came to the conclusion that there is generally a higher risk for emissions from digestates compared to non digested biomass, but they also point out that it can be easily mitigated on a storage level. As of 2012, new biogas plants in Germany are required to store digestate in a gas-tight container, which effectively limits greenhouse gas losses, primarily methane, but also N_2O and NH_3 (Vos et al. 2022; Pedersen & Hafner 2023). In contrast, the storage of manure is still very diverse and often uncovered (Oenema et al. 2007). Treating manure in a biogas plant, rather than simply storing it, is recommended as one of the most promising solutions for reducing emissions from livestock production (Pedersen & Hafner 2023).

But there is controversy among researchers about the emissions of applied digestate. The lower dry matter content of digestate is supposed to have a positive effect on infiltration into the soil and thus reduce NH_3 volatilization (Möller 2015; Pedersen & Hafner 2023). At the same time, the usually higher pH and NH_3 content in digestates seem to have the opposite effect (Möller 2015; Pedersen & Hafner 2023). Compared to untreated manure, digestate generally showed higher NH_3 losses in Møller et al. (2022), which can be partially mitigated by soil injection application technologies, but is still influenced to an uncertain extent by the climate during application, making mitigation here more challenging. (Møller et al. 2022; Pedersen & Hafner 2023).

However, the composition of the feedstock fed to the biogas plant also plays a role for the emission potential of applied digestate (Møller et al. 2022; Pedersen & Hafner 2023). Most of the research deals with digestates from animal manure and not from pure grass legume silage, as in this work (Möller 2015; Møller et al. 2022; Pedersen & Hafner 2023). However, Møller (2022) had a trial where clover grass was co-digested with manure. There, the nitrogen losses were among the highest, which was explained by the high nitrogen content of the clover grass silage, but they mentioned that emissions of the reference system were also low (Møller et al. 2022).

In case of nitrogen losses from field application, current research stands in contrast to the calculations in this thesis. Hence, the emission factor for digestate application was taken from a source, which was also used in the German national inventory report to the climate convention UNFCCC (UBA 2022; Vos et al. 2022) and can be therefore seen as national standard. Uncertainties in the emission factors cannot be completely excluded and show that there is still room for further research and improvement. Based on the arguments outlined above, there is a possibility that the emissions from grass-legume digestate could actually be higher in real life than those from applied raw manure.

To cover total farming system emissions, losses from soil management must be included. These emissions are mainly influenced by the total fertilizer input, synthetic and organic, as well as including biological fixation (Oenema et al. 2007). The emissions from soil were therefore considered in relation to the total N input in contrast to the storage and application emissions. Here, the emissions from soils fertilized with digestate had a nuance higher emissions at 19% than those fertilized with animal manure at 15%, reflecting the majority of research (Möller 2015). However, the hypotheses of the scientists are just as contradictory as in the case of application emissions. In addition, the methodology for the German inventory report in some cases even refers to the emission factor for synthetic fertilizer inputs, as there is no such factor yet for soil management, including biogas digestate (Vos et al. 2022). This shows that more research in this direction is urgently needed. Overall had the stockless system with 24% (including process losses) a bit less emissions than the stocked one (29%), outperforming the livestock system mainly by better storage technology. The scientific point of view is not yet mature enough to be able to make concrete statements about application and soil emissions.

As a fourth (iv), it should be addressed whether livestock has an impact on overall nitrogen flows and nitrogen use for net food production. The stocked system showed in general a higher quantity of nitrogen in the fluxes and therefore a larger nitrogen circulation. The optimization resulted in a higher feed production in the stocked farming model, compared to the feedstock in the stockless farming model. This meant that more nitrogen had to be taken up by the plants, which also resulted in more nitrogen entering the soil. Since both models had the same area of land available, the higher feed(stock) demand was covered by a higher proportion of forage legume cultivation, leading to a crop mix with a higher nitrogen supply. The stocked model had therefore 35% and the stockless model 26% legumes in the crop mix. However, it should be noted that the feedstock requirement is highly dependent on the composition of the feed ration and the assumptions used to calculate it, and may therefore have a significant impact on the crop mix and nitrogen fluxes (for more see chapter 5.3). But for net nitrogen utilization into food the stockless system was with 22% as percentage of the total nitrogen input more efficient than the stocked (20%). These observations go in line with the general tenor in research that farms with livestock production have a tendency to be less efficient in nitrogen utilization for food (Willoughby et al. 2022) and can be mainly explained with higher nitrogen losses in the stocked system (see iii). Therefore the high share of external nitrogen supplyers in the crop mix, like legumes, might be a way to even out the lower nitrogen utilization of the stocked system.

5.2 Food value of a stocked and a stockless farming system

The net food production showed that both the stocked and stockless farming systems were very close when it came to food production in terms of nitrogen, as discussed in the previous section 5.1. So this section addresses the optimization of produced food value, where the reference is to the total output for human nutrition. On average, the stocked system had a higher nitrogen output in food, however, this did not necessarily translate into a higher food value in terms of macronutrients, confirming Willoughby et al.'s (2022) assumption that yield does not indicate nutritional value. The stockless farming system had in the corresponding optimization scenario but also on average a more crude protein and energy dense food production, than the stocked one. In terms of crude protein, the difference was marginal, as both systems support roughly the same population. However, the stockless system provides nutritional energy for up to two more adults per ha. There is a lot of research that indirectly supports these findings for crude protein and energy production, but most of it addresses this from a feed to food conversion perspective or a dietary perspective based on land use (Alexander et al. 2016; Poore & Nemecek 2018; Ritchie et al. 2018). Willoughby et al. (2022) conducted a similar comparison of protein, fat, starch and sugar production on organic mixed farms and organic stockless farms based on nutrient input as this work did. There, the stockless farm outperformed the stocked one in protein production (Willoughby et al. 2022). They also found that the stockless organic farms had a much higher nitrogen use efficiency for protein (Willoughby et al. 2022), which even confirms the relationship between the results discussed in section 5.1 and crude protein production. Similarly, in this work, less nitrogen (total nitrogen input) was required to produce crude protein in the stockless system than in the stocked system. So crops seem to be more productive in terms of energy and protein than livestock, but there is a contradiction especially in terms of protein production. What this work does not take into account is the quality of the protein produced, which is said to be lower in grains than in animal products, lacking digestibility and essential amino acid structures (Young & Pellett 1994; Schaafsma 2000). It is therefore argued that human-digestible protein is produced more efficiently by livestock than by crops (van Zanten et al. 2016).

When it comes to fat production, the stocked system was the more consisten fat supplyer as it was able to support at least one to two more person per ha than the stockless system, regardless of the optimization scenario. Willoboughby et al. (2022) came to a similar conclusion and even showed that farming systems including livestock have the more efficient nitrogen utilization for fat. Livestock is even considered as net fat producer producing more fat than taken up by feed (Bajželj et al. 2021). Looking beyond the supply of the individual macronutrients to the overall diet provided by each farm, it is clear that the supply of fat is the limiting factor in the number of people a farm can feed. The supported population with fat was in all scenarios lower than for protein or energy. So here comes the stockless system in disadvantage, as the population supported for fat was in all scenarios even lower in in comparison to the stocked system. Globally, fat production needs to be increased, as Bajželj et al. point out, but there are also regions with excessive fat consumption where it could be halved without negative nutritional consequences (Bajželj et al. 2021). In this context, it should be noted that the optimal livestock density in this model was about a quarter of what would be legally possible (170 kg N $ha^{-1} \approx 2$ LU ha^{-1}; European Union 2018), indicating that livestock is not the core of sustainable food production but still beneficial for a farming system only relying on non synthetically fixed nitrogen.

Overall, the contribution of livestock to the nutrient supply of the models is limited because livestock is a net nitrogen consumer in form of livestock products, but more importantly, emissions. When relying on organic fertilizer alone, it should be noted that both livestock manure and biogas digestate can be a direct source of nitrogen to a crop, but not a net source of nitrogen to the farming system as a whole. Maximum macronutrient outputs were achieved in the optimisation by shifting the area distribution in the crop mix rather than by intensifying the livestock density. In the food energy optimisation, livestock density was even reduced, as plants are more efficient in producing calories than animals. In the other scenarios the livestock density remained stable and contributed about 22% to the fat production. Thus, from a holistic point of view, mixed farming systems are beneficial for quality nutrient production.

5.3 Model sensitivity, limitations and perspectives

The sensitivity analysis showed that, on average, a change in feedstock or crop mix had an effect on human nutrition of one person more or less supported, indicating that the variation in the optimization was relatively small. Thus, the sensitivity analyses revealed some variation and consequently dependencies which should be mentioned: for example, the composition of feedstock affects the crop mix and crops available for human nutrition. Restricting the feed to roughage had a negative effect on livestock density and therefore on the fat available for human consumption. At the same time it opened up land for protein-rich crops, increasing protein production in combination with a reduced livestock even above the stockless optimisation scenarios.

In turn the crop mix limits the availability of feed for livestock production. When opening up the upper constraints for crop production and therefore feed production, livestock density increased only for one animal per fattening cycle, indicating the optimum livestock density for this specific crop mix.

However, some uncertainty should be taken into account as the feed ration is calculated on dry matter only and is not optimised for energy and protein requirements. In both the original and roughage-based rations, there is a risk of energy deficiency due to the high level of protein-rich roughage and a quantitative low level of energy sources, which might slow livestock growth and productivity (Honig et al. 2020; LfL 2023). Honig et al. (2020) reached with a high energy ration a daily weight gain up to 1900 g per day. The daily weight gain chosen in this work was to be more extensive at 1100 g per day, so the variance in animal productivity should not be particularly large. Nevertheless, it might change feedstock requirements which consequently affects the crop mix and the crops available for human nutrition, requiring further research for clarification.

This work represents only a fragment of the complex processes and nutrient cycles on a farm within the food system, and should therefore be seen as a starting point for holistic research to answer the question of whether livestock is crucial for organic agriculture. In addition to nitrogen, phosphorus and potassium are essential nutrients for agriculture (Goulding et al. 2008), and organic farming tends to have difficulties in obtaining them (Berry et al. 2003). Especially strictly stockless organic farms seem to have a risk for phosphorus and potassium deficiency, as system imports through feed mainly omitted and legumes only recycle and bind nitrogen (Berry et al. 2003; Foissy et al. 2013; Willoughby et al. 2022; LtZ 2023). In this case it would be important to closer investigate stockless recycling pathways of these two nutrients, as stockless organic farms mainly rely on nutrient recycling through legumes and green manure.

Other directions for further research would be the impacts of stocked and stockless organic farming on soil organic matter as well as the impacts on the carbon cycle including important carbon related greenhouse gas emissions like methane and carbon dioxide. According to the literature seem stockless farms also have difficulties in sustaining soil organic matter (Schulz et al. 2014), which is, as mentioned in section 2.2.1, key for soil fertility in organic agriculture. Methane is one of the most reactive greenhouse gases, connected to livestock production (Martin & Sauerborn 2013), which needs especially when comparing a stocked with a stockless system to be taken into account when drawing a holistic picture of system sustainability.

A question I have asked myself while writing this thesis is whether food production and nutrient recycling is the only contribution livestock make to the food system. And yes, we know that livestock also provide many ecosystem services, such as being part of culture, maintaining landscapes and biodiversity (Karlsson 2022). Services that are already difficult to quantify, which makes them even harder to implement in a simple model like this one, but should be at least mentioned.

6. Conclusion

Current climatic and societal trends suggest that organic farming needs to re-think its dependence on livestock. This work analysed the role of livestock from a food system perspective, including not only their contribution to on-farm nitrogen management, but also the provision of macronutrients for human nutrition. The results of the stocked and stockless models were overall not far apart, due to the general structure of the model, but tendencies could be identified.

As the stockless model showed, livestock is not necessarily needed for a sufficient nitrogen cycle, especially as stockless farming systems seem to have a better nitrogen use efficiency. At the same time, the stocked systems could have had a better recycling rate if the nitrogen emissions after excretion were managed, and as the emissions from the application of biogas digestate and its characteristics in the soil are not yet clearly understood. With 15% and 20% played neither organic fertilizer from livestock nor from biogas plants a major role in nitrogen inputs to the soil, in this study. Nevertheless, depending on which stockless recycling pathway is compared to a stocked system, livestock can enable a legume-rich crop rotation and be a lucrative nutrient recycler.
In terms of individual macronutrients, the stockless system outperformed the stocked system in dietary energy with a difference of 6 GJ ha^{-1} a^{-1}, but the reverse was true for fats (difference 16 kg fat ha^{-1} a^{-1}). If fat is taken as a limiting factor for the provision of a holistic diet, the livestock farming system can supply up to 8 individuals and thus more than the farming systems without. It has been found, however, that livestock is not the major nutrient provider, instead the majority of macronutrients are supplied by the crops produced.

Whether organic farming necessarily needs livestock is debatable. This work has shown that livestock are not obsolete, particularly in providing nutrients for humans. The conclusions apply only on organic farming systems that have a similar structure to the farming systems constructed in this model. Nevertheless, this model was based on average data from German organic cash crop farms, which gives the certainty that there is a range of farming systems to which the above conclusions can be applied. However, agricultural and food systems are complex, and this work has only been able to cover a small part of them. It is therefore recommended that the effects of organic livestock systems on phosphorus and potassium cycling, soil organic matter and non-nitrogen greenhouse gases be studied and compared with those of organic livestock-free farming systems.

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Popular science summary

Nothing works in agricultural food production without nitrogen. Nitrogen is an essential nutrient for plant and animal growth, so farmers keep a close eye on their nitrogen budget and management. Like many other nutrients, nitrogen enters and leaves a farm in different forms and on different pathways. Some are intentional, some are not. For example, cops take up nitrogen from the soil, produce with it biomass which can be either sold as food or fed to livestock. The nitrogen fixed in crops sold, (intentionally) leaves the farm and must be replaced in the soil. Crops fed to livestock provide nitrogen to the animals, which is either exported in the form of animals sold for food, or returned to the soil through excreted manure, used as fertilizer. An unintentional pathway would be nitrogen lost in from manure in form of gaseous emissions as consequence of biological degradation.

There are different ways to return nitrogen to the soil. There are ways that add “new” nitrogen to the soil or pathways that recycle nitrogen that has already been in the farming system. Conventional agriculture relies primarily on new sources of nitrogen, such as synthetic mineral nitrogen fertilizers, which are known for their unsustainable production methods and also for their potential to pollute the environment. These fertilizers are prohibited in organic farming, which relies more on the efficient circulation of resources and the binding of "new" nitrogen by legumes. For the circulation of resources, especially nutrients, plays livestock an important role. Cattle, for example, can eat grass that we humans cannot and produce food as well as manure that can be used as fertilizer. Therefore, livestock is seen as the cornerstone of the circulation concept in organic agriculture, so that there is even the unwritten rule that organic farming does not function without livestock.

At the same time, livestock production is experiencing difficult times, with livestock farms declining for a variety of reasons. Livestock production is known to be one of the largest contributors to greenhouse gas emissions in agriculture. It is notorious for its inefficient use of resources, with production costs rising and regulations on farmers increasing. And then there are also ideological movements to completely renounce animal products for ethical reasons. So there is a trend away from livestock (stocked) to livestock-free (stockless) farming methods, which is not necessarily a problem in conventional agriculture because of the availability of synthetic mineral fertilizers. But in a system that relies exclusively on animal manure, such as organic farming, it might be. In this work I wanted to challenge the assumption that livestock is necessarily needed for organic farming and food production. And since nitrogen is the nutrient that farmers are most concerned about, I decided to approach this topic from a nitrogen perspective as well, asking two questions:

What is the role of livestock in sustaining nitrogen circulation in organic farming systems? How efficient are stockless organic farming systems in terms of human nutrition compared to stocked organic farming systems?

To answer these questions a quantitative biophysical model of the nitrogen cycle was built on a stocked and stockless organic farm, based on data from literature. To do this, all flows to and from the farm, all flows on the farm, and all emissions were calculated, which also provided insight into the different impacts of the production systems on the nitrogen cycle. The farm with livestock had cattle production, the farm without livestock had a biogas plant as a recycling practice. In addition, the food production performance was calculated, i.e. how much nitrogen each farming system exported in the form of crop and livestock products. To provide a broader picture of the impact of each farming system on human nutrition, food exports were converted to macronutrients such as crude protein, metabolizable energy and fat, as well as adults fed per hectare.

Both systems exported about the same amount of nitrogen as food (61 kg N ha^{-1} a^{-1}) and the size of flows in general was only slightly different. Differences could be seen for example in emissions, where the stocked system had higher nitrogen losses during storage and application, while the opposite was true for soil emissions. In both systems, biological nitrogen fixation was the main input to the soil. The stocked system had a higher share of nitrogen fixing crops in the crop rotation (35%) compared to the stockless one (26%). The stockless system produced on average more metabolizable energy and crude protein, whereas the stocked system produced more fat, which could be also seen in the supported population. In both farming systems, more individuals were supported by crude protein and energy production - while the least number of individuals were supported by fat. The stockless system supported more adults with energy, while the opposite was true for fat. Finally, the stockless system provided the same or more crude protein than the stocked system. So what do these results mean.

First, it clearly shows that to maintain the nitrogen circulation on an organic farm livestock is not necessarily needed, as organic faming systems mainly rely on nitrogen supply from cultivating legumes for nitrogen fixation. So whether livestock manure nor biogas digestate were the major nitrogen supplier. However, it should be noted that the stocked system could allow a higher nitrogen circulation if the emissions from livestock manure were improved, as it allows for more leguminous crops to be cultivated.

And as a second conclusion, an organic farming system without livestock supports more people in terms of metabolizable energy and crude protein, but not necessarily in terms of fat. When considering the whole diet, fat can be seen as a limiting factor, which would have the consequence that the livestock system would support more adults than the stockless system.

In practice, the structures of organic farming systems are very diverse, which is why these conclusions apply only to organic farming systems that have a similar structure to the farming systems constructed in this model. Nevertheless, this model is based on average data from German organic cash crop farms, which gives confidence that there is a wide range of farming systems to which the following conclusions can be applied.

Acknowledgements

I would like to take this opportunity to express my heartfelt gratitude to the people who supported and accompanied me during this Master's thesis, but also throughout my entire Master's programme.

First of all, I would like to thank Rasmus Einarsson for supervising me and my thesis. Thank you for your tireless efforts, your constructive feedback and discussions, your appreciation during our entire working process and your understanding!

Another thank you goes to Elin Röös, who was significantly involved in finding this fascinating topic and also supervised this thesis as an examiner. I would also like to mention my opponent Andrea Samuelson for her kind and valuable feedback. Thank you!

This work, but especially the whole Master's program, would not have been half as fulfilling without my dearest people here in Sweden and at home.

Thank you Mom and Dad. You both have always been there for me and believed in me. This chapter would not have been possible without you.

Appendix 1

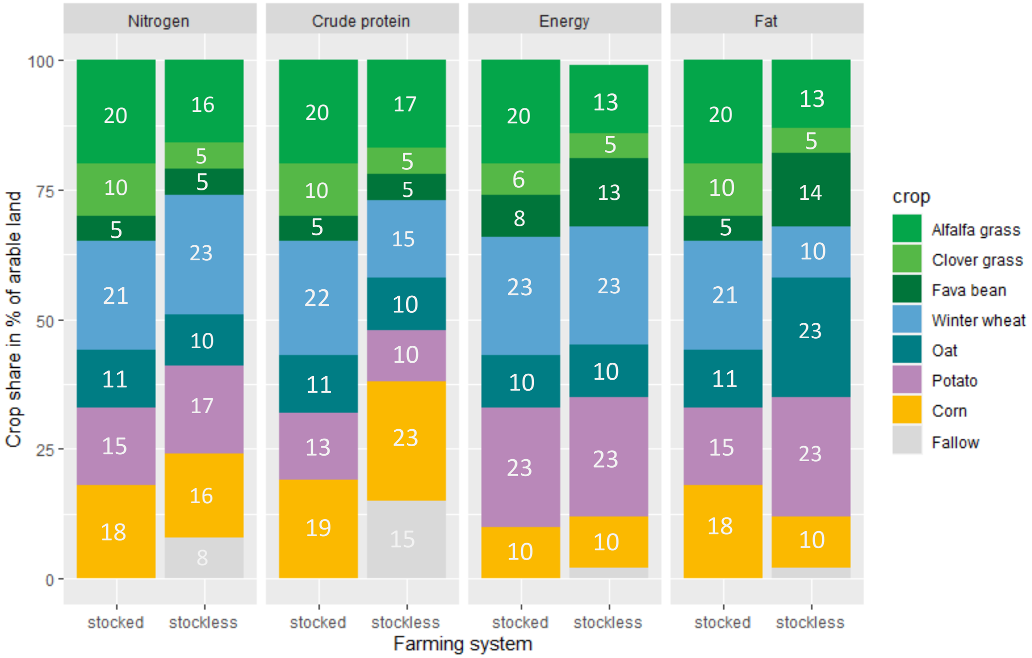


Figure 7 Crop mix according when optimizing the stocked and the stockless for each macronutrient. *Values are given as percentage of the total arable land of 220 ha*

Appendix 2

The following tables summarize the results of the sensitivity analysis described in section 3.5.2.

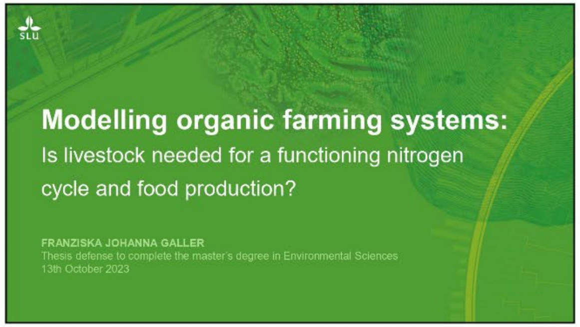
Table 10 Sensitivity analysis removing cereals from the feed ration.

		Stocked farming system				**Unit**
	Optimized for	*Nitrogen*	*Crude protein*	*Energy*	*Fat*	
Nutritional value	Total N	**68**	68	65	68	kg N ha^{-1} a^{-1}
	Total CP	319	**320**	293	319	kg CP ha^{-1} a^{-1}
	CP plant	295	296	271	295	kg CP ha^{-1} a^{-1}
	CP livestock	23	23	22	23	kg CP ha^{-1} a^{-1}
	Total GJ	87	84	**97**	87	GJ ha^{-1} a^{-1}
	Total fat	235	231	233	**235**	kg fat ha^{-1} a^{-1}
	Fat plant	197	192	197	197	kg fat ha^{-1} a^{-1}
	Fat livestock	38	38	36	38	kg fat ha^{-1} a^{-1}
Supported population	Crude Protein	18	18	17	18	Adults ha^{-1}
	CP plant	17	17	16	17	Adults ha^{-1}
	CP livestock	1	1	1	1	Adults ha^{-1}
	Energy	21	20	23	21	Adults ha^{-1}
	Fat	7	7	7	7	Adults ha^{-1}
	Fat plant	6	6	6	6	Adults ha^{-1}
	Fat livestock	1	1	1	1	Adults ha^{-1}

Table 11 Sensitivity analysis removing all upper constraints.

		Stocked farming system				**Stockless farming system**				**Unit**
	Optimized for	*Nitrogen*	*Crude protein*	*Energy*	*Fat*	*Nitrogen*	*Crude protein*	*Energy*	*Fat*	
Nutritional value	Total N	**65**	65	62	62	**63**	61	63	60	kg N ha^{-1} a^{-1}
	Total CP	326	**326**	295	299	328	**328**	323	306	kg CP ha^{-1} a^{-1}
	CP plant	289	289	260	264	328	**328**	323	306	kg CP ha^{-1} a^{-1}
	CP livestock	37	37	35	34	-	-	**-**	-	kg CP ha^{-1} a^{-1}
	Total GJ	79	79	**106**	106	111	80	**111**	107	GJ ha^{-1} a^{-1}
	Total fat	269	269	289	**291**	258	218	258	**237**	kg fat ha^{-1} a^{-1}
	Fat plant	208	208	232	234	258	218	258	237	kg fat ha^{-1} a^{-1}
	Fat livestock	61	61	57	56	-	-	-	-	kg fat ha^{-1} a^{-1}
Supported population	Crude Protein	19	19	17	18	19	19	19	18	Adults ha^{-1}
	CP plant	17	17	15	16	19	19	19	18	Adults ha^{-1}
	CP livestock	2	2	2	2	-	-	-	-	Adults ha^{-1}
	Energy	19	19	25	26	27	19	27	26	Adults ha^{-1}
	Fat	8	8	8	9	8	7	8	7	Adults ha^{-1}
	Fat plant	6	6	7	7	8	7	8	7	Adults ha^{-1}
	Fat livestock	2	2	1	2	-	-	-	-	Adults ha^{-1}

Appendix 3 – Defense Presentation



Modelling organic farming systems:

Is livestock needed for a functioning nitrogen cycle and food production?

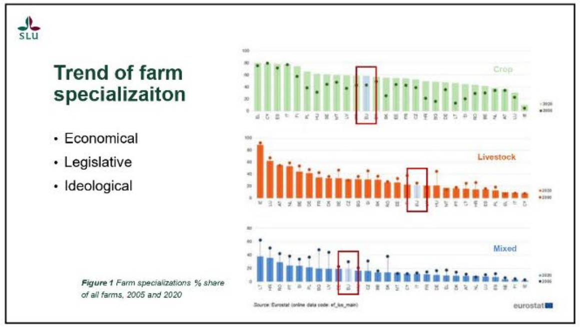
FRANZISKA JOHANNA GALLER
Thesis defense to complete the master's degree in Environmental Sciences
13th October 2023

Contents

1. The Why - Introduction and research question
2. The How - Methods
3. The What - Results
4. So What - Discussion
5. Therefore - Conclusions

The Why

Introduction and research question

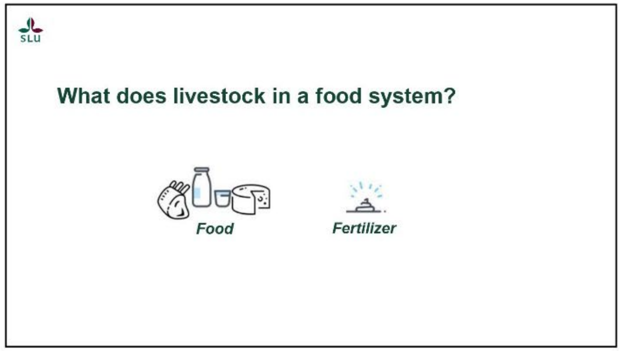


Trend of farm specializaiton

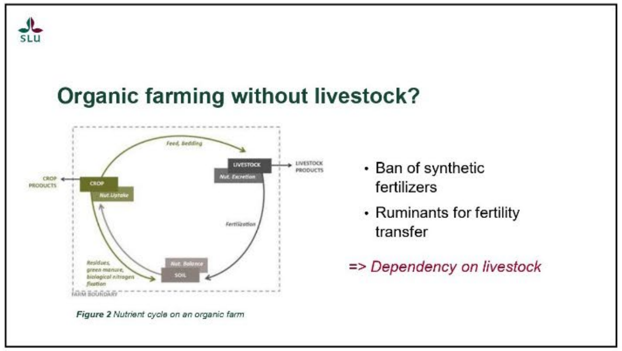
- Economical
- Legislative
- Ideological

Figure 1 *Farm specializations % share of all farms, 2005 and 2020*

Source: Eurostat (online data code: ef_kvs_main)



What does livestock in a food system?

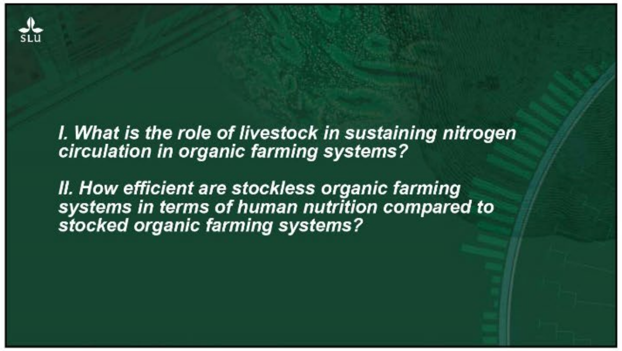


Organic farming without livestock?

Figure 2 *Nutrient cycle on an organic farm*

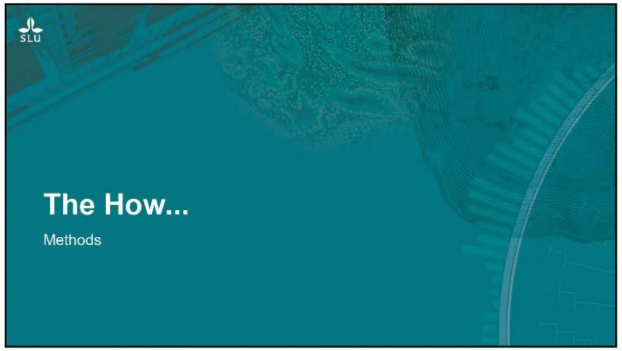
- Ban of synthetic fertilizers
- Ruminants for fertility transfer

=> Dependency on livestock



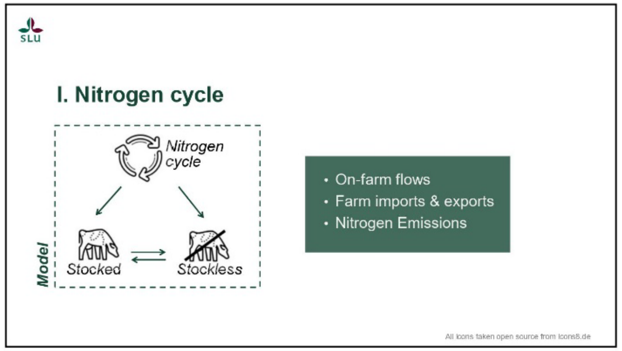
I. What is the role of livestock in sustaining nitrogen circulation in organic farming systems?

II. How efficient are stockless organic farming systems in terms of human nutrition compared to stocked organic farming systems?



The How...

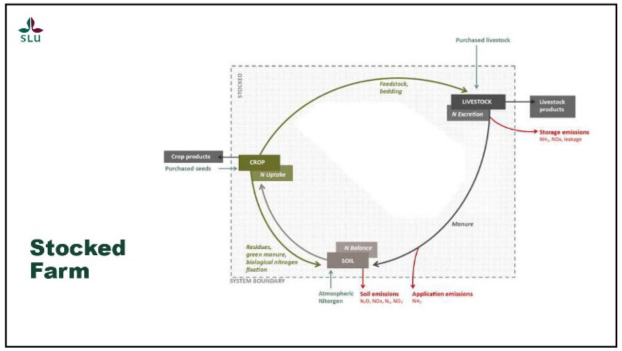
Methods



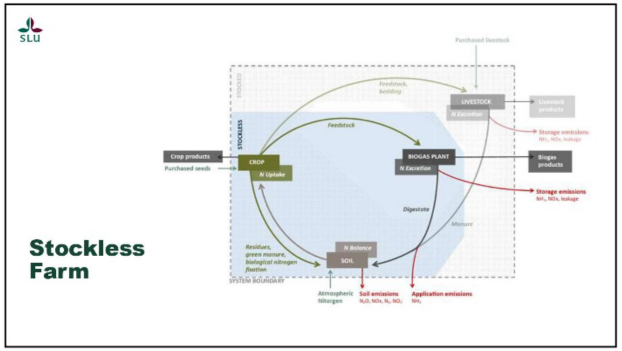
I. Nitrogen cycle

- On-farm flows
- Farm imports & exports
- Nitrogen Emissions

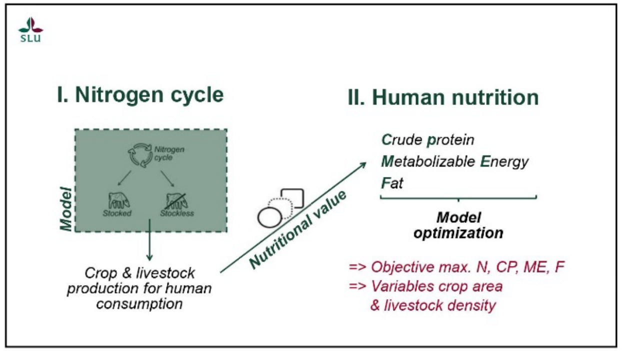
All icons taken open source from icons8.de



Stocked Farm



Stockless Farm



I. Nitrogen cycle

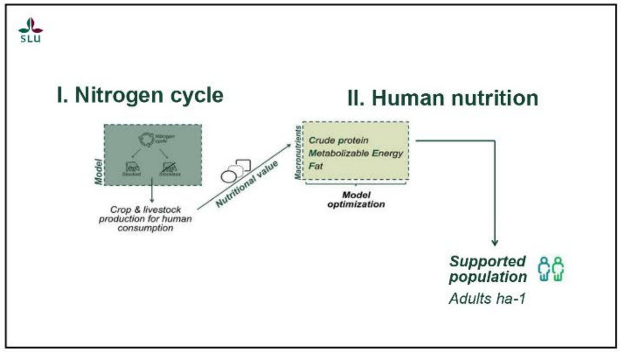
Crop & livestock production for human consumption

II. Human nutrition

Crude protein
Metabolizable Energy
Fat

Model optimization

=> Objective max. N, CP, ME, F
=> Variables crop area & livestock density



I. Nitrogen cycle

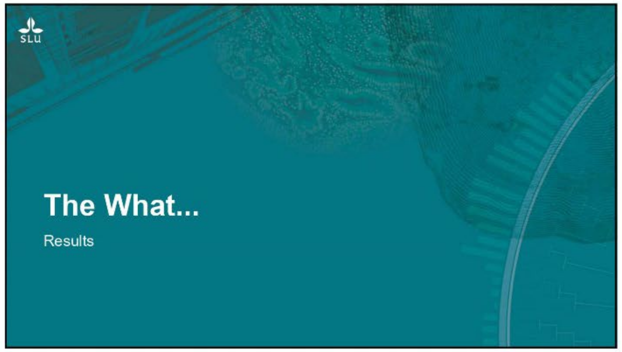
II. Human nutrition

Crop & livestock production for human consumption

Crude protein
Metabolizable Energy
Fat

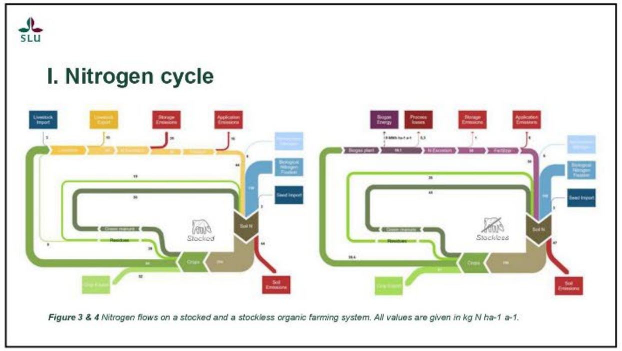
Model optimization

Supported population
Adults ha-1



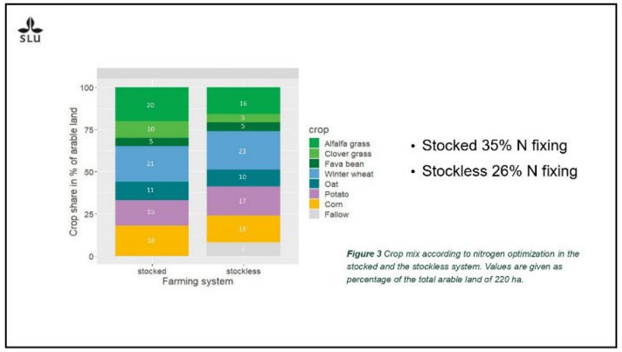
The What...

Results



I. Nitrogen cycle

Figure 3 & 4 *Nitrogen flows on a stocked and a stockless organic farming system. All values are given in kg N ha-1 a-1.*



- Stocked 35% N fixing
- Stockless 26% N fixing

Figure 3 *Crop mix according to nitrogen optimization in the stocked and the stockless system. Values are given as percentage of the total arable land of 220 ha.*

ii) How much contributes livestock to the on farm nitrogen recycling?

- Livestock net N consumer
- Nitrogen transfer of recycling process:
  - Livestock digestion: 92%
  - Biogas digestion: 100%

---

iii) What are the relative differences in nitrogen emissions between the systems?

- Storage and application emissions
  - 49% of manure N
  - 16% of digestate N
- Soil emissions of total N input
  - 19% in stockless system
  - 15% in stocked system

=> BUT uncertainty in emissions from digestate

---

iv) Has livestock an impact on overall nitrogen flows and nitrogen use for net food production?

- Larger N streams in stocked system
  - More feed production and higher legume share in crop mix
- N use for food produciton in stockless system more efficient

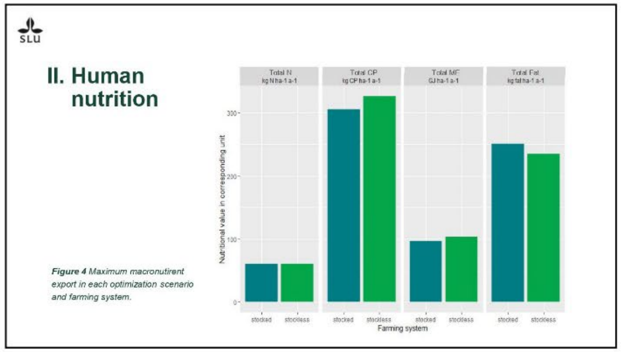
  => higher BNF partly compensates for lower N utilization in stocked system

---

II. Human Nutrition

- A larger population is supported by the stockless system with crude protein and metabolizable energy
- BUT the limiting factor for a holistic diet is fat

  => stocked system in advantage



II. Human nutrition

***Figure 4** Maximum macronutirent export in each optimization scenario and farming system.*

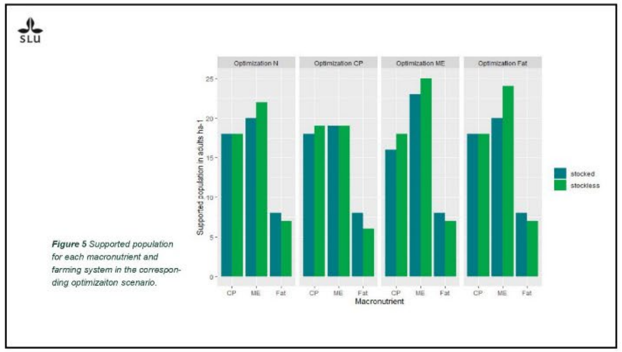
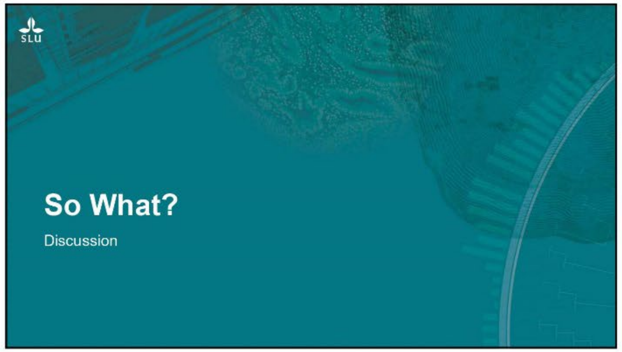
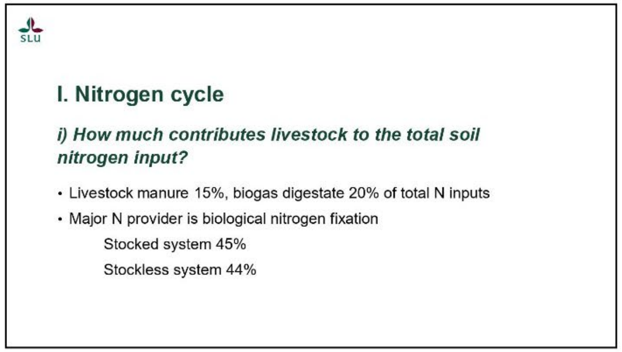


***Figure 5** Supported population for each macronutrient and farming system in the correspon-ding optimizaiton scenario.*



So What?

Discussion



I. Nitrogen cycle

i) How much contributes livestock to the total soil nitrogen input?

- Livestock manure 15%, biogas digestate 20% of total N inputs
- Major N provider is biological nitrogen fixation
  - Stocked system 45%
  - Stockless system 44%

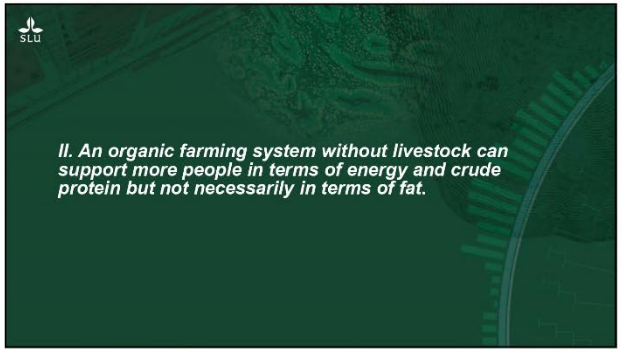
Limitations

- Model and constraint definition for optimization allow only certain margin of outcomes
    - feed and feedstock
    - crop types available
    - emission factors
- Farming systems and their processes are complex

Therefore...

Conclusions

I. Livestock is not necessarily needed for nitrogen circulation in organic farming.



II. An organic farming system without livestock can support more people in terms of energy and crude protein but not necessarily in terms of fat.

Thank you!

Supervisor Rasmus Einarsson
Examiner Elin Röös
Opponent Andrea Samuelson

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