The historic nitrogen flows of Sweden’s agro-food system

Mapping the years 1866, 1937, and 2023

Rebecca Waterhouse

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Swedish University of Agricultural Sciences, SLU
Faculty of Natural Resources and Agricultural Sciences
Department of Molecular Sciences
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Supervisor:	**Rasmus Einarsson, Swedish University of Agricultural Sciences, Department of Energy and Technology**
Examiner:	Elin Röös, Swedish University of Agricultural Sciences, Department of Energy and Technology

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Swedish University of Agricultural Sciences
Faculty of Natural Resources and Agricultural Sciences
Department of Molecular Sciences

Abstract

Nitrogen has historically been a limited resource both in natural and agricultural environments. The invention of synthetic nitrogen fixation has revolutionized agriculture, increased food production, and reduced reliance on both symbiotic nitrogen fixation and manure for maintaining soil fertility. High nitrogen losses from the agro-food system to the natural environment have resulted in serious consequences for environmental and human health, however. This study compares the current Swedish agro-food system with those of the mid-1800s and 1930s, prior to the general adoption of synthetic fertilizers and during periods of adoption and then widespread use of crop rotation systems. The aim is to understand how each period's agro-food system affected nitrogen flows, and more specifically the soil nitrogen balance in order to find out whether or not past agro-food systems were removing more nitrogen from the soil than they were putting in. The nitrogen flows of the Swedish agro-food system for the years 1866, 1937, and 2023 are measured and mapped out using an approach called the Generic Representation of Agro-Food Systems (GRAFS).

The results of the study show a large soil nitrogen surplus in 2023, a slightly positive balance for 1937, and a soil nitrogen deficit in 1866. While uncertainties are substantial, these results indicate that farmland was being depleted of nitrogen in 1866 and, to a lesser extent, in 1937. The depletion of soil nitrogen improved between 1866 and 1937, most likely thanks to the intensive use of crop rotations with leguminous crops.

Keywords: Nitrogen cycle, nutrient flow, social metabolism, GRAFS approach, agrarian history, agro-food system, Sweden

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Abbreviations

Abbreviation	Description
GRAFS	Generic Representation of Agro-Food Systems
N	Nitrogen
SM	Supplementary Materials

1. Introduction

Nitrogen is a necessary element for life on Earth. It is a determinant of plant growth, crop production, and soil fertility, and is a part of the composition of proteins and nucleic acids. Until the invention of the Haber-Bosch process in the beginning of the 20th century, only a few known microorganisms (such as certain bacteria and blue-green algae) were able to "fix" the nitrogen from the air (N_2) into the reactive forms of ammonia (NH_3) or ammonium (NH_4). Some of these bacteria have symbiotic relationships with leguminous plants, which is why their nitrogen-fixing is refered to as symbiotic nitrogen fixation. Because nitrogen-fixation has historically only been done by a few microorganisms, reactive nitrogen has historically been a limited resource both in natural and agricultural ecosystems.

Prior to the invention of synthetic fertilizers, crop rotation with legumes was the only way to fix reactive nitrogen from the air and incorporate it into the soil. Farmers could exploit pre-fixed forms of reactive nitrogen by moving onto new fertile land or by gathering nitrogen-rich material from the environment such as seaweed and placing it on cropland. Farmers can also recycle organic waste such as crop residues, manure, and human excrement. However, even when reactive forms of nitrogen are efficiently recycled within a food system, losses occur at each stage. Without nitrogen inputs in some form, the nitrogen reserves stored in soil are eventually used up if a piece of land is constantly cultivated. When nitrogen outputs in the form of crops and grazed material are greater than the inputs, the result is a negative "soil balance", or the depletion of nitrogen in the soil.

The invention of synthetic fertilizers revolutionized agriculture, reducing dependence upon symbiotic nitrogen fixation and the recycling of reactive and organic forms. This revolution came at a cost, however; the synthetic production of nitrogen fertilizers is currently the single largest cause of the human-driven intensification of the nitrogen cycle (Smil 2001:177). Once fixed into reactive forms, nitrogen becomes very mobile. The nitrogen not taken up by crops easily dissipates into the environment, entering the air, water, and terrestrial ecosystems (Erisman et al. 2013). These losses alter the nitrogen cycle and have resulted in multiple severe environmental and human health impacts (Sutton et al. 2011; Erisman et al. 2013). When nitrogen inputs to the soil (such as fertilizers) are larger than the outputs (crops and grazed material), the result is a positive soil balance. A large positive soil balance is therefore an indicator of nitrogen pollution.

This study looks at agro-food systems prior to the general use of synthetic and mineral fertilizers to see how they affected nitrogen flows. Between 1000s and the mid-1800s, 1-3 field systems were common in Sweden, and relied on outlying lands for grazing, fenced-in meadows for winter fodder, and access to manure (Myrdal & Morell 2011). In the mid-1800s, a new intensive crop rotation system was introduced in which fodder crops such as clover began being planted on cropland in rotation with food crops. This new system was its own revolution, and became the standard until synthetic fertilizers became readily available after WWII. The widespread planting of legumes on cropland should have greatly improved soil fertility and reduced nitrogen depletion of the soil.

Mapping nitrogen flows can help determine where and how much nitrogen is lost to the environment, with nitrogen loss an indicator of how efficient food systems are. A method for mapping nitrogen flows was developed in France by Billen et al. (2014) and Le Noë et al. (2017). This method, known as the Generic Representation of Agro-Food Systems (GRAFS) was used to map the current and historical nitrogen cycles of French agro-food systems (Le Noë et al. 2018). Sweden, with its cold climate, shallow soils and abundance of grass and forest differs greatly from France, and has what Hoffmann et al. (2000:278) call an "internationally unique" collection of agricultural statistics that make Sweden a good candidate for nitrogen flow modelling.

This study aims to map the historical nitrogen flows of the Swedish agro-food system. Mapping the Swedish nitrogen cycle of 1866 is interesting not only because it's as far back as the national data can go but also because it may be able determine what the nitrogen soil balance was during the transitional period between 1-3 field systems and the adoption of crop rotation and new crops such as clover in Sweden. Jumping to 1937 (a year with detailed national statistics), the nitrogen cycle should reflect the height of crop rotation in Sweden. Mapping the nitrogen cycle of 2023 will allow a comparison or our current agro-food system with those of the past.

1.1 Research questions and aim

The aim of this thesis is to map out and compare the nitrogen cycle of the Swedish food system for the years 1866, 1937, and 2023 in order to answer the following questions:

- What was the soil nitrogen balance during the periods studied?
- Was Swedish farmland suffering from nitrogen depletion in 1866 and in 1937?
- Was there a change in soil balance between the two periods, reflecting the general adoption of crop rotations with legumes?

2. Background

According to Myrdal and Morell (2011:84) continuous cropping was the norm in Sweden until around the year 1000, when the two or three-field system appeared, in which one of the fields was left fallow while the other one or two were cultivated. This system was common all over Europe and remained common in Sweden, with much regional variation, up until the late 1800s. In this system, livestock were fenced out of the cropland and foraged on communal woodland pastures. Some of the nitrogen they consumed while foraging was brought back to the farm in the form of meat, milk, and manure. Their winter fodder came primarily from a fenced-in meadow that was cut for hay and opened for grazing in late summer.

The fertilizing effect of legumes has been known since ancient times. Kjaergaard (2003:43) points out, however, that most wild legumes and food crops have a low nitrogen-fixing rate. He argues that, until the development and wide use of domesticated clover, which is more efficient at fixing nitrogen, the symbiotic nitrogen fixation that was taking place in pastures, meadows, and food crops such as peas was not suffient for avoiding a slow decline in soil fertility, especially once farmers began exporting more of their crops to cities. Sweden's growing population near the end of the 1700s and beginning of the 1800s led to an expansion of cropland, especially in southern and south-western Sweden. During this period, the nutrient balance between cropland, forests, woodland-pastures and meadows became strained, resulting in what Gadd (2000) calls "signs of ecological crisis" (2000:238). A lack of fodder meant that animal production was reduced or stagnated, while the woods receded heavily.

By the end of the 1740s, domesticated red clover had been introduced to Denmark and soon made its way over to Sweden and Finland (Kjærgaard 2003:44). It was realized that one could plant legumes such as clover and vetch and harvest them for animal fodder, and there would still be enough nitrogen left over to enrich the soil. With more fodder crops, one could feed more animals, meaning there was more manure to use as fertilizer. This led to the gradual adoption of a complex crop-rotation system.

While the earlier two and three (and sometimes four) field systems did involve the rotation of food crops and fallow, they did not usually involve the planting of fodder crops. According to Gadd (2000:308), the first fodder crop to be introduced into rotation was vetch, but during the 1830s and 1840s, grass and clover species became more common fodder crops in Skåne. By the 1860s, Osvald (1962:101) writes that crop rotation had been more or less generally adopted in the counties of Malmöhus, Kristianstad, Halland, Blekinge, Älvsborg, Skaraborg, Närke, Värmland, Bergslagen, Dalarna, and appeared even in Östergötland and Mälar county (see Figure 1). In the rest of Sweden, however, one, two, and three-field systems were still generally practiced. Gadd (2000:308–9) writes that crop rotation is thought to have become more common on larger farms in Småland by around 1870, but the two-field system still dominated among common farmers. At the beginning of the 1900s, however, these systems had been replaced by more sophisticated systems of crop rotation, with six to eight crops including fodder crops such as clover and grass.

Figure 1. The expansion of crop rotation according to Osvald (1962:101). Lighter colors represent a less generalized adoption of crop rotation. The figure is my adaption of a map from Quizlet (Landberg n.d.).

Myrdal and Morell call the integration of fodder crops on cropland “one of the great improvements brought by the Agricultural Revolution”(2011:155). The total harvest including straw, ley, and other fodder crops almost doubled between the 1870s and the end of the 1930s, mainly thanks to crop rotations where animal fodder was grown on arable land and high animal density (Myrdal & Morell 2011:185). The new farming system meant that more symbiotic nitrogen fixation was happening and more manure was available to fertilize crops, while the integrated crop and livestock farming resulted in manure being relatively evenly spread over cropland. These aspects, along with the fact that synthetic fertilizer, pesticide and herbicide use was low up until after WWII, suggest that the agriculture of the early 1900s was quite sustainable. The long-term sustainability of the relatively new technology that is crop rotation is not undisputed, however. The next section presents contrasting theories as to how the new farming system affected the nitrogen balance of farmland.

2.1 Contrasting theories

Kjægaard (2003) and Westin (2022) both write that Sweden may have been suffering from nitrogen depletion in the second half of the 1800s, but offer different explanations as to why. Kjægaard (2003) argues that European agriculture had been struggling with nitrogen depletion from the time cities appeared until the introduction of domesticated clover and its broad use in crop rotation.

The export of crops from the countryside to cities may not have been as large in Sweden as it was in other European countries, but it still may have been enough to contribute to nitrogen depletion. In 1865, The city of Stockholm had a population of 133 thousand inhabitants (Statistiska centralbyrån 1999:45).

Assuming a per capita intake of 50 g protein per day (the minimum for adults according to Bos and Tomé (2000:1)), the city of Stockholm would have been consuming around 389 metric tonnes of nitrogen every year.

Westin (2022:53–4) writes that Swedish soils began being depleted of nitrogen when farmers started plowing up the meadows that had previously been used for winter fodder in order to grow more crops, and that this soil depletion continued until the introduction of synthetic fertilizers in the 1900s. This, she explains, was due to nitrogen losses to the air and water, and to the fact that livestock were now fenced in and no longer bringing as much nitrogen back from forests and grasslands as they did during the earlier farming systems.

The plowing up of the meadows came about both during the 1800s, when cropland areas expanded, and during the 1900s, when the expansion had stopped (Morell et al. 2001:193). In the beginning of the 1800s, the expansion of cropland for food crops resulted in a stagnation or a reduction in the number of livestock due to the resulting lack of fodder. The gradual adoption of crop rotation, made possible in part by the consolidation and privatization of farmland during the second half of the 1700s and the whole of the 1800s, eventually resulted in these meadows being replaced with fodder crops as well as a rise in both livestock numbers and feed production.

Some areas took longer to adopt the new crop rotation system. In eastern Sweden, meadows were plowed under in order to plant more grain, as market prices were high. It was only when grain prices dropped in the 1870s due to international competition that farmers in this area began switching over to crop rotation and its focus on fodder crops and animal production (Gadd 2000:309).

Myrdal and Morell (2011) write that the constant growing of grain in these regions was unsustainable and only made possible by new tools, the draining of wetlands and expansion onto land previously considered unfit for crop production. They state that the new, more highly developed crop rotations generally improved fertility. They also write that the combination of better access to manure as well as to new tools, drainage technology, and expansion onto new land contributed to not only a rise in total production but also a rise in yields per hectar between the 1870s and the 1930s (Myrdal & Morell 2011:185).

2.2 Social metabolism and nutrient flows

The literature cited in this paper is from multiple disciplines, but what many of the authors have in common is their study of resources and how they both affect and are affected by societies. Society and nature are interrelated in complex ways and always have been. One way of conceptualizing this is to apply the biological concept of metabolism to social systems (Fischer-Kowalski 1998). The social or socioeconomic system is treated like an organism, which requires energy and materials, produces waste, and takes up space. The system can be considered on its own or placed in the context of the larger system within which it operates (such as the environment).

Understanding the complex relationships between society and nature requires quite a bit of simplification, and the choice of which anthropogenic material or energetic flows are studied will determine which aspects of the relationship between society and nature are brought to light. Some studies focus on outputs, such as CO_2-equivalent emissions (Garnier et al. 2019; Aguilera et al. 2021), while others consider both the inputs and outputs of a single element, such as carbon (Le Noë et al. 2019), nitrogen (Billen et al. 2014), or biomass (Soto et al. 2016). Studies can also combine flow analyses of multiple materials to gain a wider picture of socio-metabolic transition over time (Kuskova et al. 2008; Grešlová et al. 2015; Le Noë et al. 2018) or to gain a better understanding of the structure of an existing system (Le Noë et al. 2017).

This study looks at the development of Sweden's social metabolism over time by modelling nitrogen flows within the country's agro-food system. Nitrogen is an especially interesting element to study because it is a major limiting factor of agricultural primary production, a necessary component of proteins, and historically a relatively limited resource in its usable, reactive state. Nitrogen is therefore particularly useful for gaining an understanding of the biogeochemical relationships between crop farming, livestock husbandry, human nutrition, and the environment.

2.3 Nutrient budgets

A nutrient budget is defined by Einarsson (2020:13) as a "list of nutrient inputs and outputs across a system boundary in a given time period". The agricultural budgets studied in this paper are over a calendar year, and the nutrient in question is nitrogen, mainly in its reactive form (inputs), but also in its neutral form when considering symbiotic nitrogen fixation of N_2, denitrification to N_2, and emissions and losses of N_2 from manure, silage, and hay. The system boundary in this study is the agro-food system of Sweden. The aim of this paper is to determine the "balance" of the Swedish farmland soil budget for the years 1866, 1937, and 2023, in order to understand whether or not the soil of past agro-food systems was being depleted of nitrogen and whether or not crop rotations improved overall soil fertility. A balance is equal to inputs – ouputs (Einarsson 2020:14).

There are many different approaches to creating a nutrient budget and arriving at a balance, and the chosen approach depends on the purpose of the study (Oenema et al. 2003; Einarsson 2020). In this study, it would make sense to include all possible flows in order to get a complete breakdown of the different emissions from the system. However, denitrification (the microbial oxidation of NO_3^- to NO_2, NO, N_2O, and finally back to N_2) and leaching are two sources of soil nitrogen loss with relatively large uncertainties (Oenema et al. 2003).

Furthermore, the author of this study lacks knowledge in these areas and therefore prefers to speculate on the fate of the surplus nitrogen in a positive soil balance instead of attempting to calculate it. Even without calculating processes that happen below the soil surface (leaching, denitrification, and nitrogen storage), the approach used in this study should be able to give a general idea of a change in the overall soil nitrogen balance over the years 1866, 1937, and 2023.

2.4 Prior work on the subject

As stated in the introduction, this study uses the GRAFS approach for modelling nitrogen flows. Originally published by Billen et al. (2014), the method involves the collection and compilation of data on pasture, cropland, livestock, human consumption and trade combined with theoretical assumptions about the allocation of nitrogen flows from one area to another.

The work of Le Noë et al. (2017) expands the GRAFS approach to include phosphorus and carbon flows within 33 French regions, categorizing them into 5 different agricultural systems. Le Noë et al.'s subsequent paper (2018) uses the same methods to map the evolution of both farming systems and nitrogen and phosphorus flows in France from 1852 to 2014. Their results show significant nutrient losses in conjunction with agricultural specialization after WWII.
In this project, I use the methods developed by both Billen et al. (2014) and Le Noë et al. (2017, 2018) to map the modern and historical nitrogen flows of the Swedish food system. In doing so, I aim to capture Sweden's socio-metabolic transitions from a mixture of feudal farming methods and crop rotation in 1866 to the height of crop rotation and integrated animal production in 1937, to today's fully industrial agricultural system in which crop and animal production are almost entirely separate.

Swedish nitrogen flows have been studied before, but this is the first time a historical material flow analysis has been conducted for the whole country. Schmid Neset et al. (2006) quantified historical nitrogen flows for the city of Linköping going back to 1870. Einarsson et al. (2022) calculated the modern nitrogen footprint of modern Swedish food consumption. Although my study uses many of the same data sources and theoretical assumptions as the aforementioned studies, the goals and approaches are different in a few key ways. In contrast to Schmid Neset et al. (2006), this study attempts to measure nitrogen flows for the entire country. In contrast to the nitrogen footprint study by Einarsson et al. (2022), which uses a life-cycle perspective to quantify emissions of reactive nitrogen related to Swedish food consumption, this study uses a regional approach. Nitrogen flows are quantified, but not allocated to certain products. Nitrogen emissions in other countries related to imported products can be disregarded; all that matters is the net import of nitrogen in the form of fertilizer, food or feed, and where in the system the nitrogen ends up.

3. Data and Methods

In order to map the flows of nitrogen in the agro-food system for the years 1866, 1937, and 2023, data was collected primarily from national statistics and supplemented with information from other sources such as articles and books on agrarian history. Missing data was either substituted with data from the closest year or estimated using production ratios as described below.

3.1 Livestock population, production, excretion, and ingestion

Livestock play an important role in the nitrogen cycle of the agro-food system, especially in countries like Sweden, where cattle have such historical importance. In Sweden of 1866, most people outside of cities owned a cow (Israelsson 2008:11). Even if they gave little milk, the cows provided economic security and status, and could compensate for periods of malnutrition thanks to their ability to transform marginal feed resources into meat and milk (Israelsson 2008:269). Cow ownership changed over the beginning of the 1900s, and milk production gradually became the role of specialized dairies. Data on livestock are key to the GRAFS method. The following sections explain where livestock data was sourced and how it was used to calculate total nitrogen in production, excretion, emissions, and feed.

3.1.1 Livestock population

Livestock populations are provided by national statistics (Statistics Sweden 2025; Swedish Board of Agriculture 2025) and by the Swedish 2024 National Inventory Report (NIR) for the year 2022 (Swedish Environmental Protection Agency 2024b:326–340). The further back in time, the less detail is provided by national statistics. Populations for poultry, reindeer, turkey, and fur-bearing animals are missing for 1866. The hen population is estimated using the average hen to cow ratio for 1919-1961. The 1866 reindeer population is substituted with the (very steady) average reindeer population for 1885-1940. Turkey and fur-bearing populations are considered to have a low impact on total nitrogen flows and are assumed to be zero in 1866. Total population numbers for other types of livestock exist for 1877 and are disagreggated based on data from more recent years.

3.1.2 Livestock production

Data on livestock production in the form of meat, milk, and eggs is provided by national statistics (Statistics Sweden 2025; Swedish Board of Agriculture 2025), supplemented by data from Myrdal and Morell (2011). Milk production for 1866 is estimated using cow population numbers and milk yield estimates from Myrdal and Morell (Myrdal & Morell 2011:298–299). Egg production is estimated using the egg to hen ratio for 1937.

In the GRAFS method, data on meat production in terms of carcass weight is essential for determining how much nitrogen is contained in the animals slaughtered, and how much nitrogen the animals needed to consume in order to produce the given carcass weight. From the carcass weight, one can calculate how much nitrogen is available for consumption in the form of meat, and how much nitrogen is contained in the waste during slaughter. Although a certain amount of slaughter waste may have been recycled back into the food system as fertilizer during all three periods, slaughter waste recycling is not quantified in this study and is assumed to leave the food system entirely.

National statistics for carcass weight only go back to 1871, and prior to 1937, there are only two categories for carcass weight; pork, and beef/horse/sheep/lamb. This study follows the method by Le Noë et al. (2018) and uses carcass to head ratios from 1937 to both estimate meat production in carcass weight for 1866 and disaggregate the categories. Livestock production in terms of meat, milk, and eggs is then converted to nitrogen using the conversion coefficients provided by Le Noë et al. (2017).

3.1.3 Livestock excretion, manure management, grazing periods, and nitrogen emissions

Livestock excretion in terms of nitrogen is estimated using livestock population numbers and excretion rates specific for each animal category. For 2023, both livestock numbers and excretion rates come from the Swedish 2024 National Inventory Report (NIR) for the year 2022 (Swedish Environmental Protection Agency 2024b:326–340). Gaseous emissions of nitrogen from manure management (NH3, NOx, N2O & N_2) are then estimated following the guidelines of the Informative Inventory Report (IIR) for the same year (Swedish Environmental Protection Agency 2024a). The guidelines divide the nitrogen excretion of each livestock category into four manure management systems (liquid, solid, deep litter, and grazing). The guidelines then apply separate emission factors for stables, storage, and field application for the manure management system of each livestock category. Dinitrogen (N_2) emissions from manure storage are accounted for by following the EEA/EMEP Guidebook 2023 (European Environment Agency. 2023).

For 1866 and 1937, livestock population numbers come from national statistics while excretion rates for cattle, sheep, goats, and pigs come from a report by Statistiska centralbyrån (1985). Excretion rates for other animals are assumed to be the same as in 2022. Gaseous emission factors are also assumed to be the same as in 2022.

Grazing periods and manure management are adjusted based upon qualitative indications from the literature. Israelsson (2008), shows that the cows of smallholders in the latter half of the 1800s were fed low-protein fodder and often lost weight during the winter. Although actual grazing periods varied depending on the climate, weather and the availability of fodder, I have assumed that half of the nitrogen excreted by cows was excreted during grazing in 1866. This assumption is in line with that made by Schmid Neset (2005), who assumes that cattle feed in 1870 was 52% pasture, 8% cereal, and 40% coarse fodder.

As for manure management in the later half of the 1800s, manure was often piled up outdoors, exposed to the elements, while the nitrogen-rich urine seeped from barns into the surrounding soil (Morell et al. 2001:219). It is therefore assumed that all manure was managed either in solid or in deep litter form in 1866. While Le Noë et al. (2018) consider French manure management practices to be constant prior to the 1950s, Morell et al. (2001:220) write that manure management in Sweden had improved considerably by 1930, with cement platforms becoming more common under manure piles and urine being collected on some farms. The availability of livestock fodder would have also improved by 1937, with more leys being grown on cropland. It is therefore assumed that both grazing periods and manure management for 1937 follow a linear trend from those of 1866 to those of 2023.

3.1.4 Livestock feed ingestion

The amount of nitrogen produced in meat, milk, and eggs, as well as the amount of nitrogen excreted in the form of manure tell us about how much nitrogen livestock would have needed to ingest in order to produce those products. Total livestock feed ingestion is thus defined as the sum of total livestock production (meat, both edible and inedible parts, milk, and eggs) and total excretion (before gaseous losses).

When it comes to the amount of nitrogen ingested during grazing, Le Noë et al. (2017 & 2018) use French national statistics. Since Swedish national statistics do not provide this information, this study considers the amount of nitrogen consumed by livestock during grazing to be equal to the amount of nitrogen excreted during grazing. The remaining nitrogen requirements for livestock are considered to be filled by fodder crops, imported feed, and by food crops after taking into account crop consumption by humans.

Since a considerable amount of livestock feed isn't actually ingested by animals but ends up on the floor of the barn as litter, livestock apparent consumption is considered to be 5% higher than actual ingestion. This number is in line with Cederberg and Henriksson's (2020:17–18) assumptions for feed wasted by milk cows and steer, although they estimate slightly higher feed waste for other types of cattle (6%), and much higher feed waste (15%) for sheep and horses.

3.2 Losses from storage, distribution, and processing

Any nitrogen left over from crops and imported feed after subtracting the food and feed consumed by humans and livestock is considered to represent losses in storage and processing (see Figure 2). Accounting for these losses is a necessary step in modelling nitrogen flows in order to ensure that all the mass balances add up. First, total food and feed availability is calculated by adding together farmland production (grass, food, and fodder crops), animal products (carcass, milk, and eggs), and imported food and feed. Then, the apparent consumption of humans and livestock are subtracted from the total. The result should theoretically represent storage and process, but can in practice can also represent under-and over estimations in all of the involved nitrogen flows.

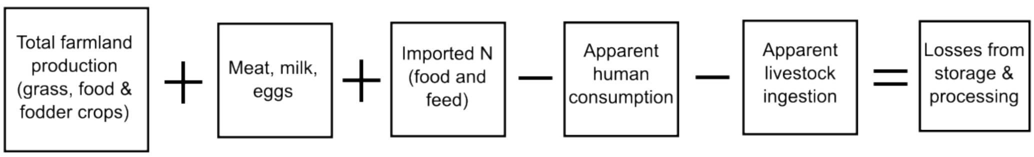


Figure 2. How losses from storage, distribution, and processing are accounted for in years 1937 and 2023

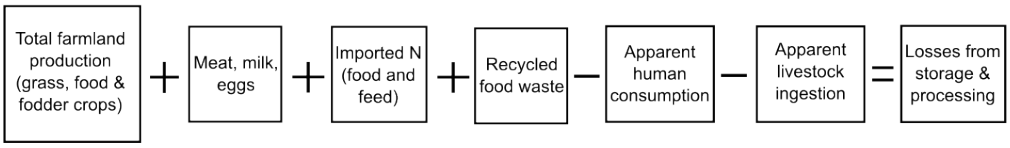
Storage, distribution, and processing losses can be large, and were probably larger in the past. This category includes most losses that happen between harvest and when products reach the consumer (besides slaughter waste, which is counted separately), or between harvest and feeding time for animals. These losses can for example be due to spoilage at any part of the supply chain, or due to waste from processing primary products into value-added products (oil seeds into oil and seedcake, grain into flour and bran/germ). Household food waste and losses during the feeding of livestock are calculated separately.

Losses during the storage, processing, and packaging of food crops are considerable. Based on waste stream estimates by Gustavsson et al. (2011) and Franke et al. (2016), Einarsson et al. (2022:8, SM1) assume that 20% of harvested quantities of potatoes, vegetables, fruits, and berries are spoiled or rejected before arriving at restaurants and grocery stores, due to spoilage and processing waste. In order to roughly estimate known losses, this study assumes that 20% of harvested fodder roots and sugar beets are lost during storage, distribution, and processing, as well as 10% of grains and 5% of pulses and oil seeds (Gustavsson et al. 2011),

Similarly to food crops, losses can also take place during the storage, distribution, and processing of livestock feed. Einarsson et al. (2022:23–24, SM1) estimate the share of nitrogen lost during silage fermentation to be 75% of the share of dry matter lost. This study assumes that around 10% of nitrogen in roughage crops (silage and hay) is lost between harvest and feeding.

In 1866, 20% of household food waste is considered to be fed to animals, as suggested by Schmid Neset (2005:82). The food waste is therefore added to the total food and feed availability of 1866 (see Figure 3). In 1937 and 2023, the fraction of food waste fed to animals is considered to be zero by Schmid Neset (2005:82), so the same is assumed in this study.

Figure 3. How losses from storage, distribution, and processing are accounted for in year 1866



Because the losses from storage and processing are the balance of such a large budget of different inputs and ouputs, a sensitivity analysis is performed to determine which factors have the largest effect on the end balance.

3.3 Farmland: pastures and cropland

One of the particularities of the GRAFS method is a differentiation between cropland and permanent grassland. International agricultural statistics define permanent grassland as grassland that has not been ploughed or cultivated in the last 5 years (EUROSTAT 2025). In Sweden, it is difficult to consistently differentiate between the two based on long-term agricultural statistics. A large quantity of grass is grown on cropland (referred to by similar studies as “temporary grassland”), and is often both mown for hay and grazed. National statistics for “permanent grassland”, which refers to areas that were grazed and sometimes mowed, but not plowed, are sparse during the late 1800s. This may be partially due to the ongoing shift at the time from communal pastures to the privatization of both cropland and pasture. In the early 1900s, the existing data for grassland areas show a myiad of different categories, including meadows that were both mown and grazed and sometimes even sown with grass and clover. In Sweden of 1866, it would have been common for animals to graze in woodland pastures, where leaves and lichen could be eaten in addition to grass (Morell et al. 2001:227; Westin et al. 2022). Areas of land that were mown and/or grazed by animals are referred to in this paper as “pasture”, since grass is and was not the only type of plant growing in these areas.

Due to the complexities in differentiating between cropland and pasture, this study treats it all as one category, farmland. However, in order to calculate the total area of farmland, one must know the areas for cropland and permanent pasture. National statistics on total cropland area exist during the whole period, even if the area may have been greatly underestimated, with statistics gradually improving until around 1913 (Holgersson 1974). In Table 1, the cropland area used in this study is compared with cropland areas from other sources, illustrating the uncertainty surrounding national statistics during this period. The largest area, Holgersson's (1974:47) estimate, is 50% larger than the smallest area, from JO1901B0.

Table 1. Comparison of statistics on cropland areas for 1866

Source	Cropland area (1000 hectares)	Notes
This study	2 218	Same sum as the line below + 20921 hectares "Tree, hop, and cabbage garden" from JISFTGAGL
JO1901B0	2 197	Sum of the categories listed as cropland
JO1901B0	2 153	Area listed as total cropland
HISTA01	2 387	
Holgersson (1974:47)	3 223	Average for 1865-1869

This study uses the sum of the cropland areas listed in the Swedish Board of Agriculture's table JO1901B0 (2012) augmented with the area listed as "tree, hop, and cabbage garden" from table JISFTGAGL for 1866 (Swedish Board of Agriculture 2007). By 1937, national statistics tables agree on a cropland area of around 3.7 million hectares. This study augments the area slightly by adding the area for "vegetable and fruit gardens" (32 072 hectares) from table JISFTGAGL for 1932 (Swedish Board of Agriculture 2007).

Statistics on permanent pasture do not exist until 1981. For prior years, the areas for the categories "natural meadow" (1891) and "other grazing land" (1937) are chosen to represent permanent pasture.

3.3.1 Nitrogen inputs to farmland

The nitrogen inputs to farmland considered in this study are synthetic fertilizers and guano, atmospheric deposition, manure, recycled human excreta, some recycled food waste, seeds, and symbiotic nitrogen fixation.

Synthetic fertilizer and guano

Data on synthetic fertilizer usage in agriculture in terms of metric tonnes nitrogen are available from national statistics for the years 1989-2023. For the year 1937, nitrogen inputs from synthetic fertilizer were sourced from Berglund (1956:15), who sourced his data from national statistics. For the earliest period, 1866, the fertilizers imported were most likely guano from South America (Gadd 2000:314). Since nitrogen quantities in guano vary depending on the source and what it was treated/blended with, the fraction of nitrogen contained in the guano imported in 1866 is considered to be the same as that of the total mass of fertilizers used in 1938/1939, which was 4,9% (Grahn 1961:60). Of the nitrogen embedded in both imported guano and in synthetic fertilizers, 2% is assumed to be lost via volatilization (Swedish Environmental Protection Agency 2024b:350, Table 5.28).

Atmospheric deposition

Nitrogen inputs from atmospheric deposition for the current period are calculated by multiplying the total farmland area by the deposition rate for 2022, sourced from Statistics Sweden (2022a). Deposition rates for 1866 and 1937 are assumed to be similar to those used by Schmid Neset (2005:85) and are set at 0,95 kg N/hectare and 2 kg N/hectare farmland respectively. Schmid Neset (2005) bases her estimates on those of Hoffmann (1999), who calculated historic nitrogen leaching for different areas in southern Sweden between 1865 and 1995.

Manure

Nitrogen inputs from manure are estimated to be equal to the total amount of stored manure applied onto fields after emissions (NH3, NOx, N2O & N_2), which are estimated following the guidelines of the Informative Inventory Report (IIR) for the year 2022 (Swedish Environmental Protection Agency 2024a).

Human excreta

Morell (2001:221) states that the use of human excreta was common place during the second half of the 1800s, and that both human and horse excreta was particularly important for the market gardens surrounding cities. Nitrogen inputs to farmland through recycling of human excreta (sludge) in 2023 is calculated based on national statistics for 2022 (Statistics Sweden 2022b). For 1866 and 1937, the recycling of human excreta is based on Schmid Neset's (2005:82) estimates for 1870 and 1940.

Food waste

Food waste recycling was also calculated using Schmid Neset's (2005:82) estimates, which are the following: in 1866, 70-90% of food waste was assumed to be recycled back to the soil while 10-30% was fed to animals. In 1937, 40-60% of food waste was assumed to be recycled back into the soil, and the rest was assumed to go to landfill. In the current period, food waste recycling was considered to be zero, even though a certain amount of nitrogen from anaerobic digestion and household compost is indeed recycled back into the soil.

Seeds

A part of total crop production must be set aside each year for planting the next year. The nitrogen contained in seeds and seed tubers is estimated using the method described by Le Noë et al. (2018:SM1 p. 17), who estimates seeds to account for 2% of cereal harvests, and 5,6% of all oleaginous, proteaginous and dry vegetables for the current period. For 1900 and earlier, Le Noë et al. (2018) estimate seeds to account for 17% of cereal harvests and 10% of all oleaginous, proteaginous, and dry vegetables. The values are interpolated linearly between the years 1900 and 1990, with seed/harvest ratios considered to be constant before 1900 and after 1990.

Symbiotic nitrogen fixation

Symbiotic nitrogen fixation is estimated roughly following the method used by Le Noë et al. (2017:SM1 p. 14-15). The fixation is estimated by multiplying nitrogen yields of forage and grain legumes by 1,47 and 1,23 respectively. Temporary pastures and meadows are assumed to be made up of 15% forage legumes in 2023 and 1866 and 25% forage legumes in 1937. These proportions are uncertain, but the proportion for 2023 is in line with current estimates (Frankow-Lindberg 2003; Einarsson et al. 2022). At the height of crop rotation systems in 1937, forage legumes are assumed to have a larger importance and therefore take up a larger proportion of temporary pastures.

Le Noë et al. (2017) assume legumes to be responsible for 25% of the total nitrogen production in permanent pastures for all years, giving the following equation:

Symbiotic N fixation from permanent pasture = pasture N production x 0,25 x 1,47

As stated in section 3.1.4, however, there are no good Swedish statistics on the production of permanent pastures, although some estimates exist (Juréen 1942). This study uses grazing periods to estimate the amount of nitrogen ingested by livestock during grazing, which helps describe the overall production of farmland but does not describe precisely how much of that grazed plant material came from permanent pastures. Because livestock graze on both temporary and permanent grasslands as well as roadsides and on fallow land, the legume fraction in the equation above is considered to be the same as that for temporary pastures (15% in 2023 and 1866 and 25% in 1937) to reflect the probable proportion of legumes in temporary grasslands during each of these periods. The resulting equations used in this study are the following:

1866, 2023: *Symbiotic N fixation from grazed plants = grazing N ingestion x 0,15 x 1,47*

1937: *Symbiotic N fixation from grazed plants = grazing N ingestion x 0,25 x 1,47*

3.3.2 Nitrogen outputs from farmland

Production of food, fodder, and even industrial crops are included in the overall production of farmland, since industrial by-products such as oilseed cakes and distiller's grains often end up becoming feed. Data on crop harvests, harvest areas, and yields are sourced from national statistics. Missing data is substituted with data from other years or simply left out if the area or production is small, and when a reasonable production estimate cannot be found. The nitrogen contents of different crops are taken from Einarsson et al. (2022:SM2), who primarily source nitrogen crop contents from the Swedish Board of Agriculture's database VERA, used for calculating nitrogen farm budgets.

The nitrogen content of horticultural crops is estimated by taking the average of the top five horticultural crops by production volume for 2023. The production and yield of horticultural crops for 1866 and 1937 is estimated using a power trendline from existing data.

As stated in section 3.1.4, the amount of nitrogen consumed by livestock during grazing is assumed to be equal to the amount of nitrogen excreted during grazing. The nitrogen contained in crops and grazed plant material by dry or wet weight, depending on the data, is considered to be constant for the periods studied. The nitrogen contained in crop residues is not accounted for in this study since the net flow to and from fields is likely to be small (Einarsson et al. 2022:15, SM1).

3.3.3 Soil nitrogen balance

The nitrogen balance of farmland soil is defined as the sum of nitrogen inputs minus nitrogen outputs. As shown in Figure 4, the nitrogen inputs included in the study are imported guano and synthetic fertilizers, manure, human excreta and recycled food waste after accounting for nitrogen losses, symbiotic nitrogen fixation by legumes, the nitrogen contained in seeds, and atmospheric deposition. Nitrogen outputs are crops and grazed plant material. The soil nitrogen balance is an indicator of likely nitrogen losses and/or soil nitrogen depletion. A negative balance (a deficit) implies that more nitrogen is removed than added, so that the soil is gradually depleted of stored nitrogen. A positive balance (a surplus) indicates soil nitrogen accumulation and/or nitrogen losses through denitrification (N2, N2O and NO) and leaching (NO_3^- and some organic nitrogen). Because there are inevitably some losses through denitrification and leaching, a small positive nitrogen balance is necessary to guarantee that the soil is not gradually depleted of stored nitrogen. Leaching and denitrification are not taken into account in this model, but are discussed in the discussion section. Because this balance is central to the study, a sensitivity analysis is performed to determine what factors have the largest effect on the resulting balance.

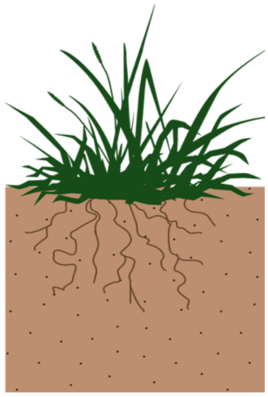


Figure 4. The soil nitrogen balance is equal to the sum of soil nitrogen inputs minus soil nitrogen outputs. This figure was created using art from the Swedish University of Agricultural Sciences' media bank for staff and students.

3.4 Trade

Data on the import and export of food and agricultural products is sourced from national statistics. Exports are subtracted from imports to get a net import in tonnes for each product category. For 2023, average import and export statistics for 2021-2023 are sourced from SITC 5-digit international trade statistics (Statistics Sweden 2024b; c). Nitrogen contents of imported and exported products are taken from Le Noë et al. (2017:SM1, 3–8) and supplemented with other sources as needed.

3.5 Human population, consumption, and excretion

Total, urban and rural population figures are provided by Statistics Sweden (2024a). For all periods studied, the conversion coefficients used to translate food protein into nitrogen are taken from Le Noë et al. (2017) and supplemented by coefficients from CIQUAL (https://ciqual.anses.fr/), the Swedish Food Agency (2025), and other sources as needed. For 2023, apparent consumption (the total availability of primary products for human consumption) is sourced from statistics gathered by the Swedish Board of Agriculture (2024). Actual ingestion (the food actually consumed by people after taking into account inedible parts and household waste) is estimated from a dietary study conducted in 2010-2011 by the Swedish Food Agency (2012). Food waste is then defined as the difference between apparent consumption and actual ingestion.

For 1937, both apparent consumption and actual ingestion are estimated based upon national dietary studies conducted in 1940 among urban and rural households (Statistics Sweden 1941a; b). The dietary studies give high per capita results for consumption in kg nitrogen and are therefore assumed to represent apparent consumption. In order to estimate actual consumption, proportions for inedible parts and household waste are estimated using waste factors from Einarsson et al. (2022).

Since no national statistics on consumption exist for 1866, both apparent consumption and actual ingestion are taken from Schmid Neset et al. (2006:66), who estimated nitrogen flows in kg nitrogen per capita for the city of Linköping in 1870. These estimates may be a bit low due to the fact that they are based on urban consumption. The nutritional studies of the 1940s show rural consumption to be higher than urban consumption. 1866 was a period of low yields, however, making it more likely that Schmid Neset's (2006) estimates for 1870 are a good fit for national per capita nitrogen consumption in 1866.

4. Results

4.1 Livestock population, production, excretion, and ingestion

In this section, the results for the different parts of the food system are described in the same order as in the Data and Methods section. The results are then summarized in a flow chart of the whole system, after which special focus is paid to the soil nitrogen balance and storage and processing losses.

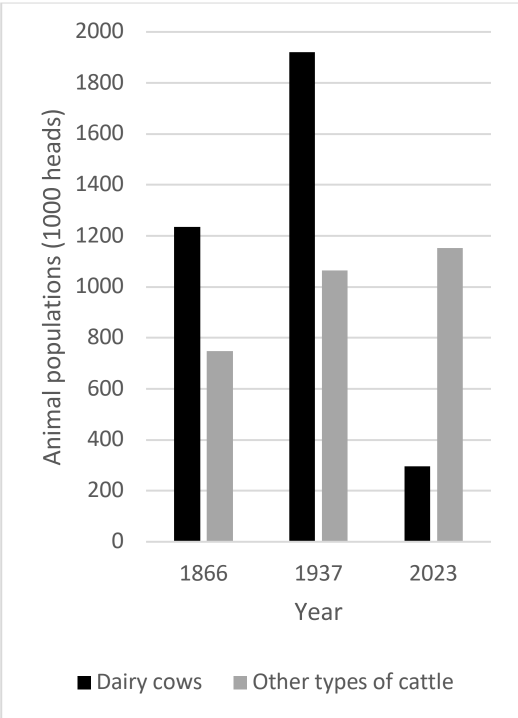


Figure 5. Main animal populations, 1866, 1937, and 2023 in thousands of heads

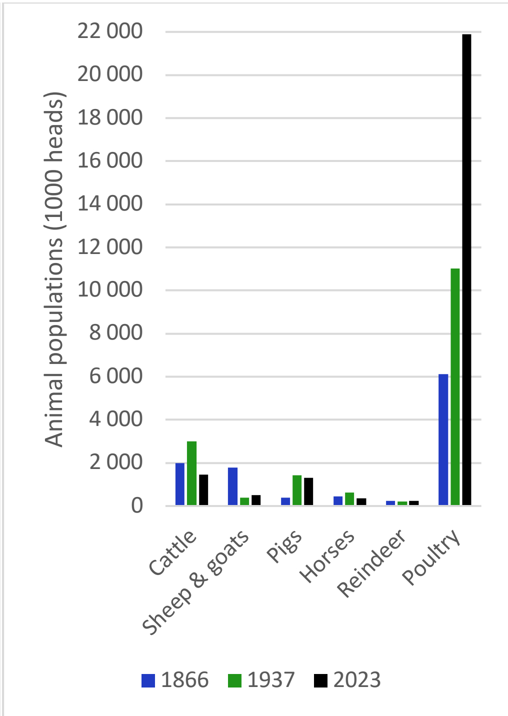


Figure 6. Dairy cow populations relative to other cattle categories, 1866, 1937, and 2023 in thousands of heads

Of the three periods, cattle populations were at their highest in 1937, when the majority of cattle were dairy cows (see Figure 5 and Figure 6). Pig and poultry populations have grown over the periods studied, with poultry populations nearly four times higher in 2023 than they were in 1866. Sheep and goat populations shrunk drastically between 1866 and 1937, and have remained small. Horse populations were highest in 1937 of the three periods. Reindeer populations have varied little over the three time periods.

Livestock production for 1866, 1937, and 2023 follow a trend similar to that of livestock population numbers, as illustrated in Figure 7. Both meat and egg production has grown over time, whereas milk production was at its highest in 1937 out of the three periods.

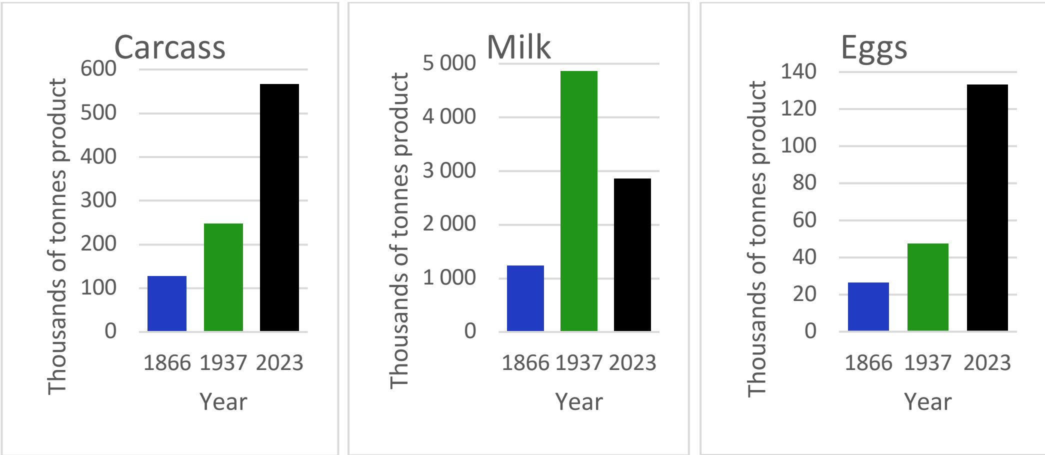


Figure 7. Livestock production in the form of carcass, milk, and eggs. (thousands of tonnes product).

Figure 8 shows the total livestock production for each year studied, in thousands of tonnes nitrogen. Figure 9 shows the total nitrogen excreted by livestock and the related emissions in thousands of tonnes during each of the periods studied. Livestock excretion and emissions were highest in 1937.

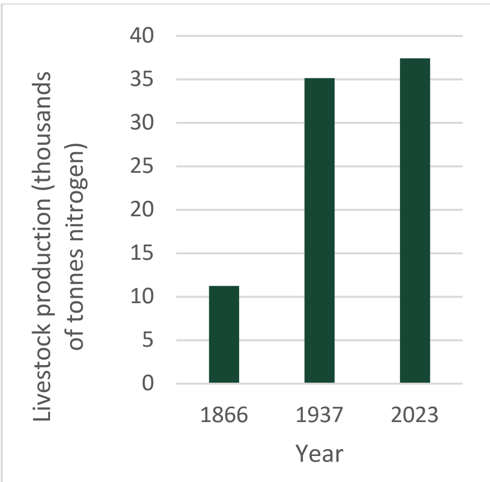


Figure 8. Livestock production (carcass, milk, eggs) in 1866, 1937, and 2023 (thousands of tonnes nitrogen)

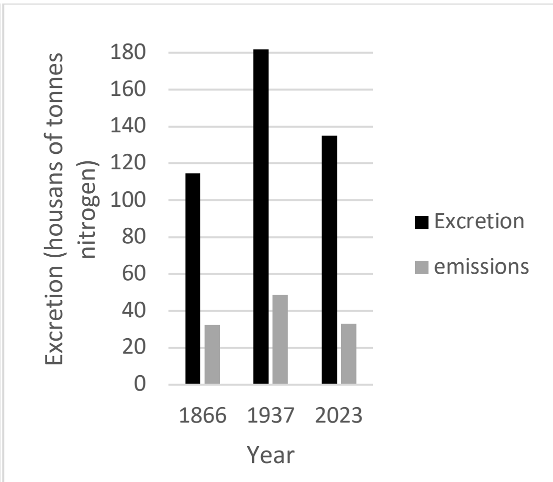


Figure 9. Livestock excretion and emissions in 1866, 1937, and 2023. (thousands of tonnes nitrogen).

The actual feed ingestion and apparent feed consumption for the three periods are shown in Figure 10.

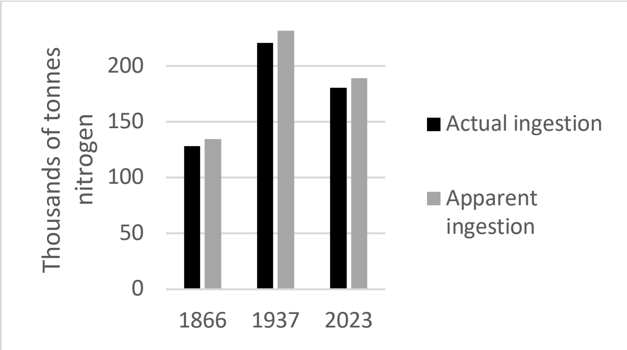


Figure 10. Actual livestock ingestion and apparent livestock consumption for years 1866, 1937, and 2023. (thousands of tonnes nitrogen).

4.2 Farmland: pastures and cropland

Out of the three periods studied, total farmland areas were largest in 1937 and smallest in 2023 (see Figure 11). Permanent pasture areas made up close to half the farmland area in 1866. By 2023, permanent pasture areas had shrunk to less than a third of what they were in 1866.

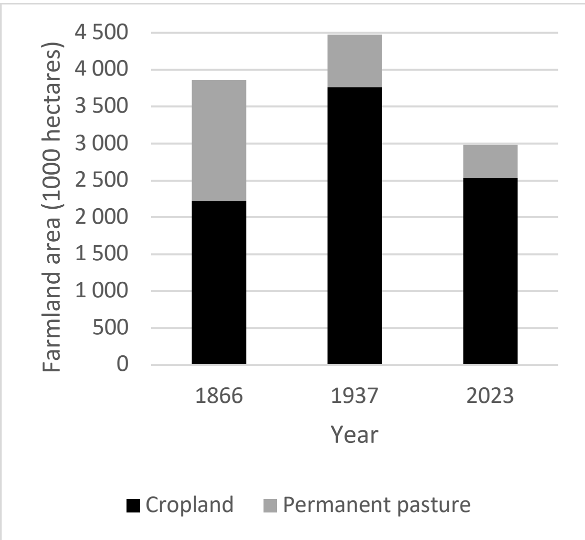


Figure 11. Total farmland areas in 1866, 1937, and 2023, divided into permanent pasture and cropland

Figure 12 shows cropland areas by crop type for each of the years studied. There is a visible reduction in fallow area over time, but fallows did not disappear completely. Morell (2001:201) explains that, even after the adoption of crop rotation systems, fallows maintained their importance everywhere in Sweden except in southern Sweden and in Norrland, as fallows helped manage weeds and maintain soil structure. Areas for grain are about the same in 2023 as they were in 1866, but the area devoted to leys is larger in 2023. In both 1937 and in 2023, the area devoted to leys and silage crops together is nearly equal to the area devoted to all other crops with the exception of fallow.

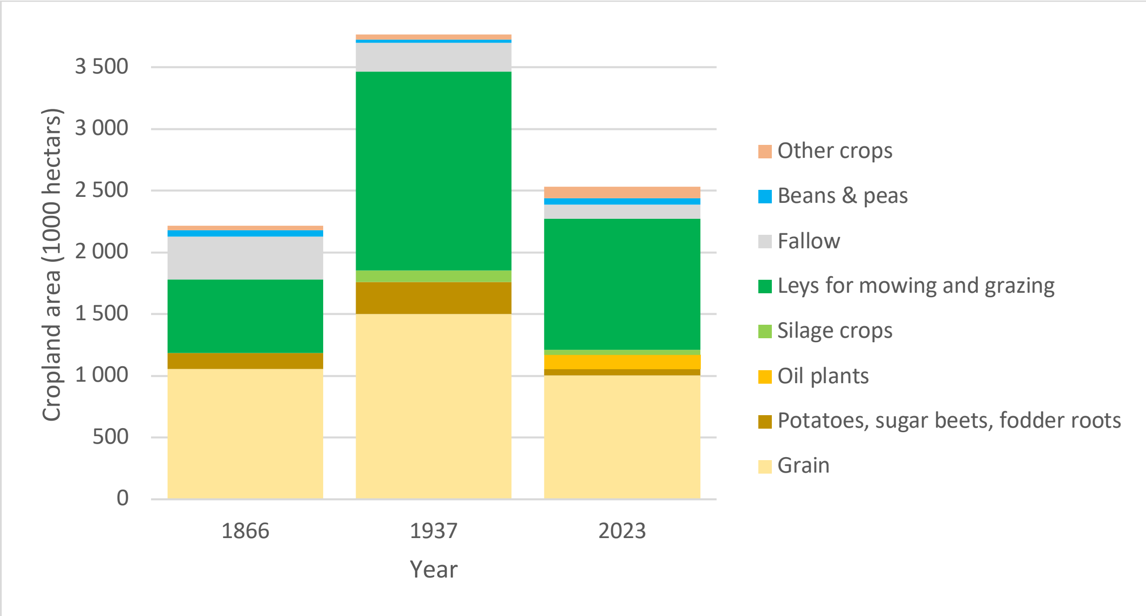


Figure 12. Cropland areas by crop type for 2023, 1937, and 1866 in thousands of hectares

4.3 Results summary flow chart

The results of the study are summarized in Figure 13. The following sections take a closer look at the results for the soil nitrogen balance, processing and storage losses, and total nitrogen losses from the system model.

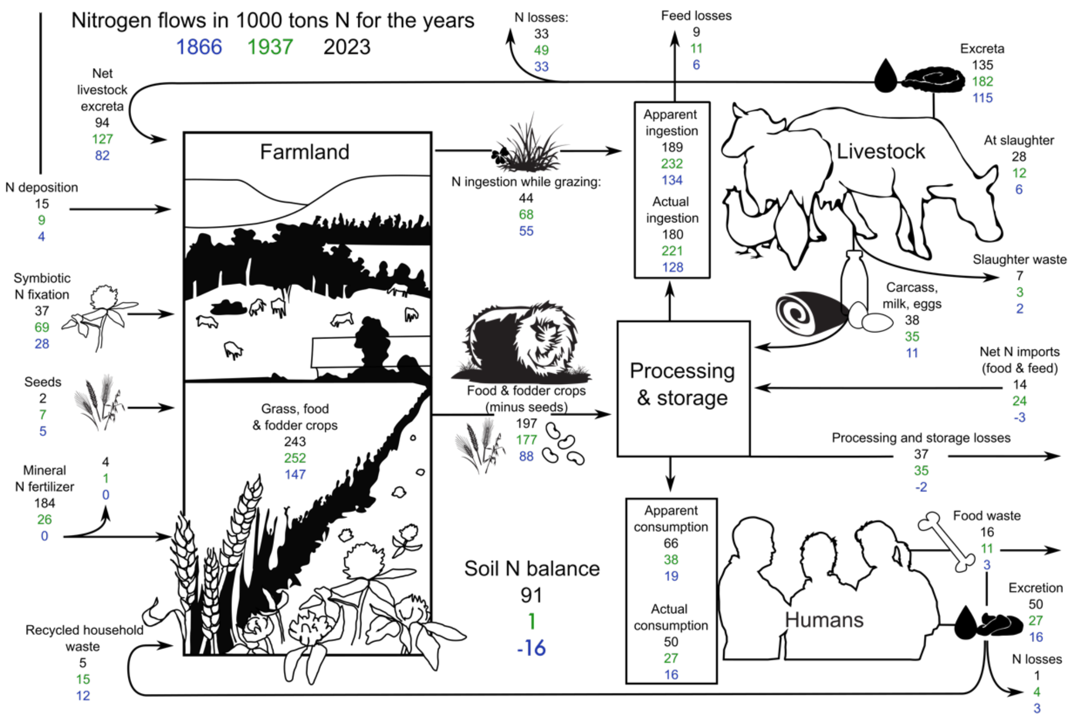


Figure 13. Nitrogen flows in thousands of tonnes for the years 1866, 1937, and 2023

Nitrogen amounts are given in blue for 1866, in green for 1937, and in black for 2023. The figure was created using art from the Swedish University of Agricultural Sciences' media bank for staff and students as well as Microsoft Word's icon library).

4.4 Nitrogen inputs and outputs and the soil nitrogen balance

Figure 14 displays the nitrogen inputs and outputs to farmland by type, and Figure 15 summarizes the resulting soil balance for each of the years. The results for 2023 show a large soil nitrogen surplus of 91 thousand tonnes. This is slightly higher than the soil nitrogen surplus calculated by Statistics Sweden (2022a), who found a soil balance of 87 thousand tonnes nitrogen for the year 2022. Unlike this model, however, Statistics Sweden (2022a) did not take into account the inputs of symbiotic nitrogen fixation from permanent pasture. The results for 1937 show a low soil nitrogen balance of 0,6 thousand tonnes, while in 1866, the results show a soil nitrogen deficit of -16 thousand tonnes.

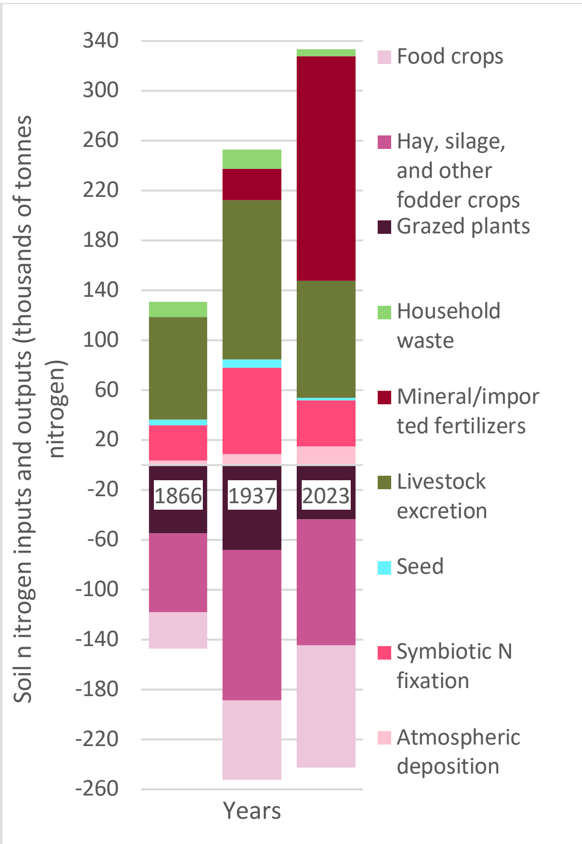


Figure 14. Nitrogen inputs and outputs to farmland for 1866, 1937, and 2023 in thousands of tonnes nitrogen

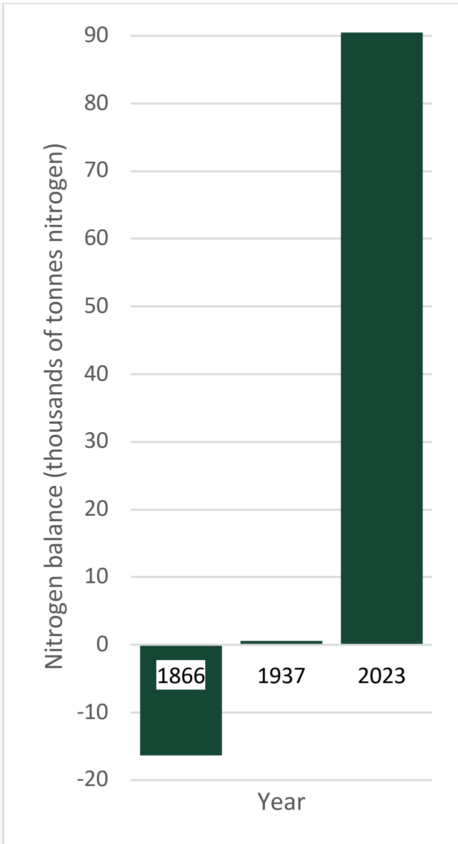


Figure 15. Farmland nitrogen soil balance for 1866, 1937, and 2023 in thousands of tonnes nitrogen

The large nitrogen surplus in 2023 represents large nitrogen losses to the environment, although some nitrogen is stored in the soil. The negative soil balance of 1866, on the other hand, indicates that more nitrogen was being taken out of farmland than was being put back in, supporting the theory that the soil was being depleted of nitrogen during this period. The slightly positive soil nitrogen balance 1937 was probably not enough to account for nitrogen losses via leaching and denitrification, though this topic is discussed in the discussion section.

4.4.1 Sensitivity analysis effects on the soil nitrogen balance

As shown in Table 2, legume shares of leys, meadows, and grazed plants are a primary determining factor of the soil nitrogen balance. Increased legume shares add more nitrogen to the system through symbiotic nitrogen fixation. When legume shares for 1866 and 2023 are adjusted to the same level as in 1937 (25% for leys, meadows, and grazed plants), the soil nitrogen balance for 1866 becomes positive, while the balance for 2023 is grows to 110,2 thousand tonnes nitrogen, 20 thousand tonnes higher than the original results when legume shares were at 15%.

Table 2. Sensitivity analysis effects on the soil N balance of farmland (thousands of tonnes nitrogen per year)

	2023	1937	1866
Study results	90,5	0,6	-16,4
Legume share of leys, meadows, & grazed plants - 20%	84,6	-12,8	-19,0
Legume share of leys, meadows & grazed plants + 20%	96,4	14,1	-8,6
Legume share of leys, meadows & grazed plants + 30%	99,4	20,8	-6,0
Legume share of grazed plants at 25% all years	96,9	0,6	-5,8
Legume share of leys, meadows & grazed plants at 25% all years	110,2	0,6	3,5
Livestock excretion rates +10%	96,4	9,0	-12,4
Livestock excretion -10%	84,5	-7,8	-20,3
Crop production - 10%	107,5	14,0	-9,2
Crop production +10%	73,5	-12,8	-23,5
Crop production + 20%	56,5	-26,3	-30,7
Less household waste to plants, more to animals	90,5	-2,4	-17,9
More household waste to plants, less to animals	90,5	3,7	-14,8
Livestock ingestion from grazing +10%	87,1	-3,7	-16,4
Ruminant grazing periods multiplied by 1,2	91,7	4,4	-14,9
Ruminant grazing periods multiplied by 0,8	89,3	-3,2	-17,8
Human actual ingestion & apparent consumption, +10%	90,5	2,1	-15,1
Human actual ingestion & apparent consumption, -10%	90,5	-0,9	-17,6

The soil nitrogen balance is also increased when livestock excretion rates are increased and when crop production is lowered, meaning less nitrogen is being harvested in the form of crops. It is unlikely that crop production was overestimated in this study because both Einarsson et al. (2022) and Statistics Sweden (2022a) found higher results for the current period (

Table 3).

Table 3. Comparison of farmland production results

Category	Thousands of tonnes nitrogen
Study results for total farmland production	**243**
Einarsson et al. (2022) average for years 2015-2017:	277
Statistics Sweden (2022) for year 2022:	266

Due to the model assumptions having to do with the fraction of recycled household waste during the different periods (see section 3.2.1), increasing waste recycling has a larger effect on raising soil nitrogen balances in earlier years than in the modern period. The same goes for increasing human apparent consumption and actual ingestion, since this translates to more food waste and excretion available for recycling.

Increasing ruminant grazing periods interestingly increases the soil balance. Since other excretion factors remained the same, increasing ruminant grazing periods increases total excretion, resulting in more manure being deposited on pastures. Since grazing periods and ingestion from grazing are connected in this model, this change also means that ruminants consume more nitrogen in the form of grazed plants. Because nitrogen emissions are lower for livestock excretion deposited while grazing than they are for manure deposited indoors and stored prior to application to cropland, however, the result is a net increase in the overall soil nitrogen balance.

4.5 Storage, distribution, and processing losses

As explained in section 3.1.4, storage, distribution, and processing losses are simply the accounting result when animal and human consumption are subtracted from total available food and feed. Some processing and storage losses are to be expected, so the result should be positive. The results show surprisingly large storage, distribution, and processing losses for 2023 (37 thousand tonnes nitrogen) and 1937 (35 thousand tonnes nitrogen), with a negative value for 1866 (-2 thousand tonnes nitrogen). The negative results for 1866 show that the modelled nitrogen flows of food and fodder crops and imported food and feed were insufficient for covering the apparent consumption of both humans and livestock. This negative result indicates that nitrogen amounts from crop production, plant ingestion via grazing, and feed imports may have been underestimated in the model, or that animal production and excretion were overestimated. These different possibilities are tested out in the sensitivity analysis.

4.5.1 Sensitivity analysis effects on processing and storage losses

The results of the sensitivity analysis are shown in Table 4. An overestimation of human apparent consumption and actual ingestion is an unlikely possibility, since human ingestion is based on Schmid Neset's (2005) already low urban consumption estimates for 1870. The small amount of food waste that the model allocates to livestock feed had no significant effect on storage and production losses. An overestimation of livestock excretion rates is possible. It is unlikely, however, that livestock populations were overestimated, since Israelsson (2008) shows that national statistics on cattle populations are reliable, indicating that other livestock populations may also have been well-counted.

Table 4. Sensitivity analysis effects on processing and storage losses (thousands of tonnes nitrogen per year)

	2023	1937	1866
Study results	37,2	35,0	-2,4
Apparent livestock consumption at 106% of actual ingestion	35,4	32,7	-3,7
Apparent livestock consumption at 110% of actual ingestion	28,2	23,9	-8,8
Livestock excretion rates +10%	27,5	22,7	-9,0
Livestock excretion -10%	47,1	47,2	4,1
Crop production - 10%	17,5	17,2	-11,2
Crop production +10%	56,9	52,8	6,4
Crop production + 20%	76,6	70,6	15,2
Livestock ingestion from grazing +10%	41,6	41,8	3,1
Ruminant grazing periods multiplied by 1,2	45,7	48,4	8,3
Ruminant grazing periods multiplied by 0,8	28,8	21,6	-13,1
Human actual ingestion & apparent consumption, +10%	30,6	31,1	-4,3
Human actual ingestion & apparent consumption, -10%	43,8	38,8	-0,5

Another possible explanation for the negative result for 1866 is an overestimation of apparent feed consumption. Much like humans, livestock don't eat all the food they are given. Some falls on the ground and gets trampled, some gets thrown into the air to disperse flies, and some may get eaten by mice. Losses during feeding could have been lower in 1866 than they were in 1937 and 2023, due to an overall lack of feed. The lack of feed meant that cattle and other ruminants were often given feed that was low in nutrients, such as straw of different kinds, that was primarily used as litter in later years (Israelsson 2008). Because of its low-nitrogen content and use in litter, nitrogen from straw is not accounted for in total crop production. Instead, it is assumed to mostly return to the soil. Perhaps nitrogen in straw should be accounted for as feed in 1866.

An overestimation of apparent feed consumption in the mid-1800s would likely be offset by larger storage and production losses due to less efficient harvesting and storage systems. Furthermore, the default percentage used in this model for apparent livestock consumption (5% of actual ingestion for all animals all years) is a little low when compared Cederberg and Henriksson's (2020:18) estimates for young cattle (6%), sheep and horses (15%). It is therefore more likely that the model underestimates feeding losses.

Of all the above possibilities, an underestimation of crop production is most likely. National agricultural statistics are known to be unreliable until around 1913, and as previously discussed, Holgersson's (1974) study shows that cropland areas may have been undestimated by as much as 50% in the 1860s (Table 1). As for the large positive processing and storage losses in 2023 and 1937, these may be partially explained by taking a look at known losses.

4.5.2 Known losses

The estimated known losses from food and feed during storage, distribution, and processing are shown in see Table 5. These known losses equal about 20 thousand tonnes nitrogen in 2023 and 1937.

Table 5. Storage, distribution, and processing losses, by type (thousands of tonnes nitrogen)

Category	1866	1937	2023
Study results for storage and processing losses	**-2,4**	**35**	**37**
Estimated losses for silage, hay, and other fodder crops	6,3	12	10
Estimated losses for potatoes, sugar beets, fruits, vegetables, grains, pulses and oil seeds	2,7	7	10
Sum of estimated losses	**9,0**	**19**	**20**
Difference	-11,4	16	17

One can conclude from Table 5 that the possible overestimation of storage and processing losses for the years 2023 and 1937 is in the range of 17 and 16 thousand tonnes nitrogen respectively. Meanwhile, 1866 shows a total underestimation of 11,4 thousand tonnes nitrogen. Closing these budgets is difficult, even when the data is plentiful, as is the case in 2023, and the question deserves further research.

4.6 Total nitrogen losses from the system model

Figure 16 gives an overview of all of the nitrogen flows that are considered to leave the Swedish agro-food system. Parts of some of these flows, such as feed waste, may actually find their way back into the food system. The total of all of the losses (positive amounts only), give a result of 47 thousand tonnes nitrogen losses in 1866, 122 thousand tonnes losses in 1937, and 241 thousand tonnes losses in 2023. Nitrogen emissions from livestock excretion were the same in 1866 as in 2023, and were highest in 1937, reflecting not only higher livestock populations but also less efficient manure handling methods than during the modern period.

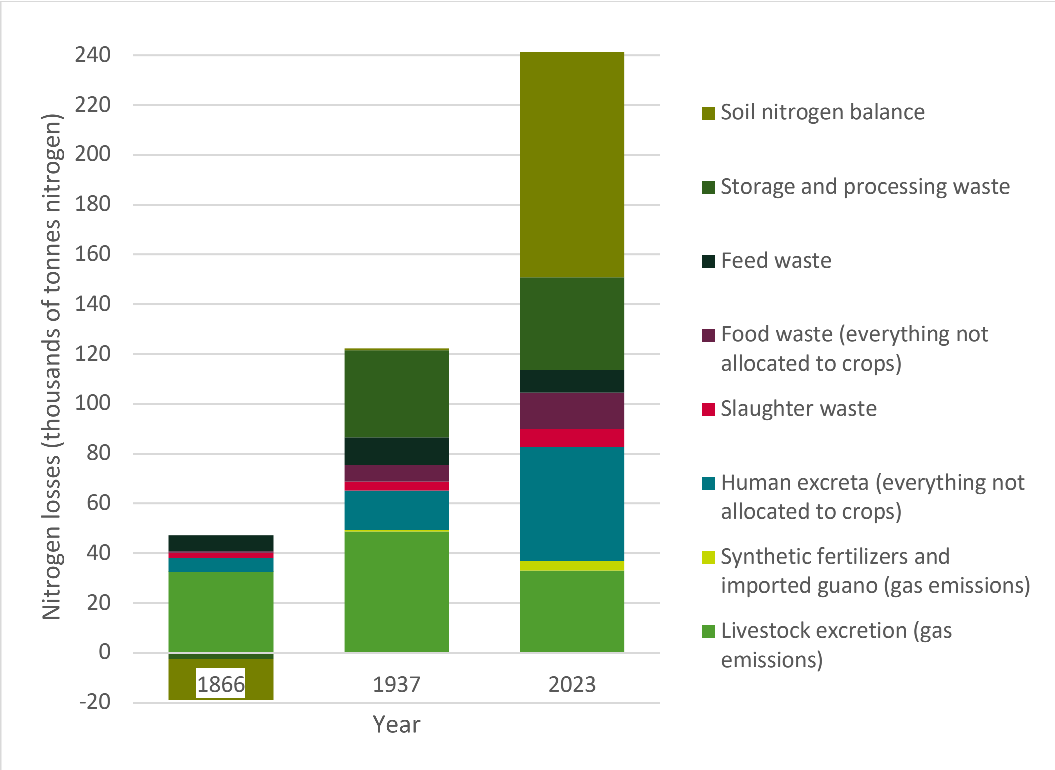


Figure 16. Nitrogen losses from the system model, by type and year (thousands of tonnes nitrogen)

Sweden's population has increased significantly over the three periods, as have total production and consumption, so it is unsurprising that nitrogen losses have increased over the three periods. When divided into kg per capita per year, the losses are still smallest in 1866 (11 kg), larger in 1937 (19 kg), and largest in 2023 (23 kg) (see Figure 17). The difference between the years becomes larger when total nitrogen losses are divided by total farmland area (Figure 18).

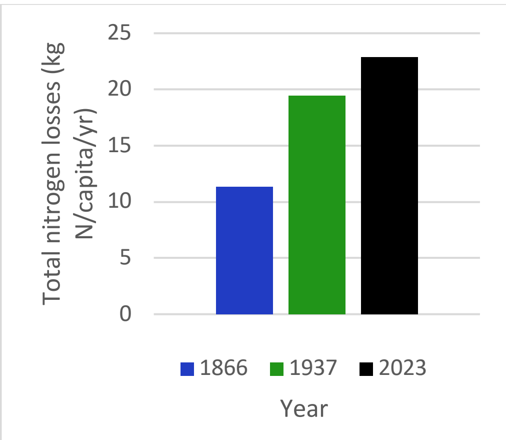


Figure 17. kg nitrogen losses per capita per year

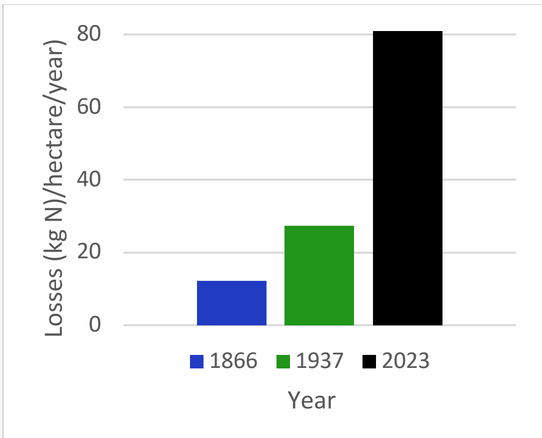


Figure 18. kg nitrogen losses per hectare farmland per year

5. Discussion and Conclusion

5.1 What the soil nitrogen balance leaves out: leaching, denitrification, and nitrogen stored in soil

Nitrogen losses from leaching and denitrification were not accounted for in this study. A study by Hoffmann et al. (2000) estimates both historic nitrogen leaching and gross nitrogen load from arable land in south and central Sweden between 1865 and 1985. Hoffmann et al. (2000:288) define gross load as “all the specific leaching rates for different regions summarised for the whole country”. South and central Sweden were chosen for their study because the production areas are “relatively uniform with respect to cultivation practices and conditions for crop production” (1998:482). Hoffman et al. (2000:286) found that leaching rates in south and central Sweden in the middle of the 1800s were somewhere between 20 and 32 kg nitrogen per hectare, depending on assumptions of mineralisation and denitrification rates. The ‘Normal’ scenario presented by Hoffmann et al. (2000:286) shows a leaching rate of approximately 27 kg nitrogen per hectare cropland in 1866. Hoffman et al. (2000:277) explain that these high rates were due to large areas of bare fallow, low yield, and enhanced mineralization from newly cultivated land. Hoffman et al. (2000:281) specify that “assumptions concerning the amount of organic nitrogen in the soil profile and the mineralisation rate are decisive to the result of the calculated leaching estimates”, and quote national statistics showing cropland to have increased by 1,3 million hectares between 1865 and 1935.

Holgersson (1974), whose estimate for cropland area in the 1860s is shown in Table 1, writes that the area of land reclaimed between 1865 and 1911 was only 465 thousand hectares (Holgersson 1974:22), and quotes slightly higher statistics for cropland expansion (1,35 million hectares), despite the shorter time period. He concludes that the remaining hectares are not an expansion of cropland but rather a statistical fiction, representing the gradual improvement of national statistics. If Holgersson (1974) is correct, and the expansion of cropland happened much earlier than what is shown by national statistics, then the leaching estimates by Hoffmann et al. (2000:286) could be much lower than the ‘Normal’ scenario presented in their study, in which 60% of the increase in cropland is assumed to have originated from the ploughing up of old grassland.

Of course, if Holgersson’s (1974) estimates are correct, they have implications not only for the study by Hoffmann et al. (2000) but also for the results of the current study, especially with regards to crop production. As far as leaching is concerned, however, if only 465 thousand hectares of grassland were reclaimed as cropland (Holgersson 1974) out of the total cropland “expansion” of 1,3 million hectars between 1865 and 1935 (Hoffmann et al. 2000), then the resulting fraction is 36%. Leaching rates may therefore have been closer to the 'Low' scenario presented by Hoffmann et al. (2000:282, 286), in which 20% of the increase in cropland originated from the ploughing up of old grassland and a high denitrification rate (0,64) was assumed, resulting in a leaching rate of around 21 kg nitrogen per hectare in 1866.

Supposing this rate was the same for cropland all over Sweden (not just in the southern and central parts), then total leaching from cropland in Sweden (using cropland areas from this study) would be equal to around 47 thousand tons nitrogen. Hoffmann et al. (2000:286) show gross nitrogen load estimates for the 'Low' and 'Normal' scenarios to vary between 50-65 thousand tons nitrogen in 1866 and 57-62 thousand tons nitrogen in 1937 (see Table 6).

Table 6. Soil nitrogen balance results from this study compared with leaching rates and gross load ('Low' and 'Normal' scenarios from Hoffmann et al. (2000)

Year	Soil nitrogen balance (thousands of tonnes)	Leaching rates (kg N/ha/yr)	Total soil losses (thousands of tonnes)	Source
1866	-16	21-27	50 to 65 (gross nitrogen load)	(Hoffmann et al. 2000)
1937	1	17-18	57 to 62 (gross nitrogen load)	(Hoffmann et al. 2000)
2023	91	17	44 (total leaching from farmland, year 2022)	SCB 2022

The statistics used in this study show an expansion in the acreage of leys and temporary pastures of about 1 million hectares between 1866 and 1937. Had this expansion happened on land that was previously sown in annual crops, the transition to leys would have resulted in an increase in soil carbon content and thus a small increase in soil nitrogen stocks (Bolinder et al. 2018). As explained above, however, at least 465 thousand hectares (probably more, since expansion continued up until around 1930) was previously grassland, forest, or wetlands, whose higher carbon and nitrogen content would have begun decreasing once ploughed under. When soil organic matter declines, mineralisation is larger than the input of new organic material, resulting in a likelihood of increased nitrogen losses through leaching, denitrification, and harvest export (Hoffmann et al. 2000:281). It is therefore unlikely that there was any net gain in soil nitrogen stocks between 1866 and 1937.

Between 1937 and 2023, however, cropland receeded by almost as much as it had expanded (at least on paper) in the 1800s and early 1900s. The area to leys receded by 551 thousand hectares and the area devoted to crops receded by 683 thousand hectares. Meanwhile, the fraction of cropland devoted to leys is nearly the same in 2023 as it was in 1937 (44% and 43%, respectively). The land use transition from cropland to permanent pasture and forest would have resulted in a gradual increase in soil organic matter, and thus an increase in soil nitrogen stocks in these areas. If the relatively high % of cropland in leys was maintained between 1937 and 2023, then cropland soil nitrogen stocks may also have increased slightly, but a more precise estimate requires more research.

Hoffmann et al. (2000:283) refer to denitrification as "the most uncertain sink of N" in their study. Because nitrates in the soil can be subject to both denitrification and leaching, they explain, a large amount of denitrification decreases the amount of nitrogen available for leaching. Drainage projects began in the early 1800s in Sweden, first with the building of large, open ditches and then with the tiling of fields. By 1920, a quarter of all cropland was tiled (Morell et al. 2001:215). Improved soil drainage extended the growing season and made nutrients more readily available to crops (Morell et al. 2001:214). It also would have reduced denitrification rates and thus increased the amount of nitrogen leached from the soil. Add to this the draining of about 2500 lakes, and the result is an overall decline in the retention of nitrogen and a net increase of nitrogen lost to rivers and seas (Hoffmann et al. 2000:288).

Despite uncertainties regarding leaching rates, denitrification, and the expansion of cropland, one can safely conclude that nitrogen depletion was a problem in both 1866 and 1937.

5.2 Other nitrogen flows not accounted for in this study

Domestic fish production/harvest is not accounted for in this study, and is hard to measure, which is why it is currently even left out of national statistics. Net imports and consumption of fish do make up a part of total nitrogen imports and food consumption in the model, however. Not accounting for domestic fish production may help explain the negative result for processing and storage losses for 1866 but might also inflate modern loss results further. Although domestic fish production is probably only a small part of total nitrogen flows, the study could be improved by either removing fish entirely or by estimating domestic production.

The nitrogen amounts contained in crop residues, straw, recycled food waste in the form of compost and fertilizer from anaerobic digestion, and any eventual recycling of slaughter waste were left out of the flows in this model. Crop residues and straw mostly get recycled back to the soil, and any losses to the environment are considered insignificant relative to the larger nitrogen flows in the system. Home composting is difficult to measure, but fertilizer produced from anaerobic digestion for the modern period could be added to recycled nitrogen flows. Another source of recycled nitrogen that could be included in the overall model (but currently is not) is livestock feed waste, a portion of which most likely ends up in litter and eventually returns to the soil.

5.3 Possible sources of error and further research opportunities

5.3.1 Farmland areas and production

As illustrated in Table 1, national statistics for crop production, area, and yield as well as for permanent pasture areas do not always match up, and sometimes contain conflicting information. Crop, area, and yield categories and definitions have changed over the years, making it difficult to construct detailed time series. It would be interesting to redo the study using Holgersson's (1974) study as a basis for re-estimating total farmland production.

5.3.2 Grazing and fallows

Contrary to the assumptions having to do with grazing periods in this study, "grazing" or scavenging for food directly from the earth was not only done by cows, sheep and goats, but also by pigs and probably poultry. Morell (2001:228) writes that most often sheep and sometimes pigs were allowed to graze on fallow land as soon as plants started sprouting on it in the spring. Since grazing intake is determined by grazing periods, it might be appropriate to add "grazing" periods to the study for monogastrics in 1866 and possibly even in 1937. Doing so would decrease the amount of nitrogen ingested in the form of feed, and increase the overall ingestion from "grass", even if that nitrogen in fact came from insects. Not having included "grazing" periods for monogastrics might help explain the lack of feed availability in the model for 1866, resulting in negative storage, distribution, and processing losses.

"Fallow" land was sometimes sown with grass seed or even alfalfa, as was the case in Öland (Morell 2022:228). A certain amount of symbiotic nitrogen fixation would thus have happened on fallow land, that was not accounted for in this study.

5.3.3 Apparent consumption and actual ingestion

In this study, human actual ingestion in terms of nitrogen was calculated in kg per capita from nutritional studies and then multiplied by the total population at the time. Since children eat less than adults, this may result in an overestimation of actual ingestion for 2023. Lowering human actual ingestion in 2023 would only result in increasing food waste, which is considered to leave the system in 2023. The study could be improved by estimating food waste recycling in 2023. For 1937, the nutritional studies were on a household basis, meaning they represented the average consumption of adults and children together. Actual ingestion in terms of nitrogen for 1866 is the least certain, since it's based upon the consumption of the citizens of Linköping in 1870 (Schmid Neset 2005).

5.3.4 Variability in yearly statistics

Since national statistics for crop and animal production and trade can vary greatly from year to year depending on weather, international politics, and statistical accuracy, it is often best to get an average of several years' data. This study includes an average net import for 2021-2023, but otherwise relies on national statistics for single years. While this certainly affects the reliability of the results, it is not always possible to get an accurate average for past years. Often, detailed statistical surveys were conducted every five years, with less-detailed surveys done in between. Nonetheless, this study could be improved by taking a multiple-year average for each category for which data exists.

5.3.5 Determining symbiotic nitrogen fixation

Symbiotic nitrogen fixation is a complex process that depends upon a large number of variables, including crop type, age, soil type, temperature, and nutrient availability (Høgh-Jensen et al. 2004). No one really seems to know exactly what percentage leguminous crops are grown on temporary and permanent pastures, and how much nitrogen they fix, though estimates exist. In this study, legumes were assumed to make up 15% of both temporary and permanent pastures, which gives lower results for total symbiotic nitrogen fixation than those found by Statistics Sweden (2022a) and Einarsson et al. (2022), whose results are summarized in Table 7.

Table 7. Comparison of estimates for symbiotic nitrogen fixation (tonnes nitrogen)

Source	Thousands of tonnes nitrogen
Statistics Sweden, for 2022 (cropland, adjusted for grazing)	39,6
Einarsson et al. (2022), for 2015-2017 (cropland only)	49,8
This study, for 2023 (cropland and permanent pasture)	**36,9**
This study, 2023, at 18% legumes (cropland and permanent pasture)	42,8
This study, 2023, at 19,5% legumes (cropland and permanent pasture)	45,8
This study, 2023, at 25% legumes (cropland and permanent pasture)	56,6

The above comparison leads to the conclusion that the assumed legume fraction of 15% is too low, and may actually be as high as 25%, especially since neither Statistics Sweden (2022a) nor Einarsson et al. (2022) take into account symbiotic nitrogen fixation on permanent pastures. 25% legumes is the fraction used for 1937, and it may be too low. More research is needed to determine more precise legume fractions. The study could possibly be improved by using a different method for estimating symbiotic nitrogen fixation.

5.4 Conclusion

The aim of this thesis was to map out and compare the nitrogen cycle of the Swedish food system for the years 1866, 1937, and 2023. The resulting nitrogen flows show a large positive soil balance in 2023, a balance close to zero in 1937, and a negative soil balance in 1866. The results for 1866 support the hypothesis from the literature that the farming methods used during this period were depleting nitrogen from the soil. The results for 1937 support the hypothesis that the crop rotation system of the early 1900s was able to improve soil fertility, although not enough to avoid nitrogen depletion of the soil. Certain aspects of the modell deserve more research, such as the fraction of legumes planted as leys, as well as the fraction of legumes in pastures and meadows. There are many uncertainties related to the model, especially in terms of symbiotic nitrogen fixation and total farmland production, and questions remain as to how to appropriately close the budget for storage, distribution, and processing losses. This study could be improved in many ways, especially by calculating out leaching, nitrification, and soil nitrogen accumulation for all periods and by calculating uncertainties in nitrogen budget inputs and outputs. Despite the many questions and uncertainties, the nitrogen flows modelled in this study suggest that crop rotations with legumes made a significant positive difference in the soil nitrogen balance between 1866 and 1937.

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Popular science summary

Nitrogen is a necessary element for life on Earth, a determinant of plant growth, crop production, and soil fertility, and a part of the composition of proteins and nucleic acids. Although 78% of the atmosphere is made up of nitrogen gas, the triple bond between the nitrogen atoms makes it hard for most living organisms to make use of. Only a few known microorganisms (such as certain bacteria and blue-green algae) are able to break the bonds of nitrogen gas and “fix” it into reactive forms. This is why nitrogen has historically been a limited resource for plants, animals, and agriculture. Certain plants, known as legumes, have a symbiotic relationship with nitrogen-fixing bacteria, providing carbohydrates in return for nitrogen. This process is called symbiotic nitrogen fixation, and until less than a century ago, planting legumes was an important method for keeping farmland fertile.

The invention of synthetic fertilizers revolutionized agriculture but came with a cost. Reactive forms of nitrogen are easily lost to the air and water, ending up in the environment instead of in our food. Too much reactive nitrogen in the wrong places has negative impacts on human and environmental health and contributes to climate change. When more nitrogen is applied than crops can take up, the result is a positive soil “balance”, or a surplus of nitrogen. A large surplus of nitrogen implies nitrogen pollution.

Past agricultural systems have struggled to keep nitrogen in the soil. When more nitrogen is taken out of the soil in the form of crops and grazed material than what is put in, the result is a negative soil balance, or the gradual depletion of nitrogen from the soil. This study looks at the period between the mid-1800s and WWII, during which a new intensive crop rotation system was adopted in Sweden, to see if crop rotations with legumes improved soil fertility and reduced nitrogen depletion.

In order to test this theory, this study uses an approach called the Generic Representation of Agro-Food Systems (GRAFS) to map the flows of nitrogen between pastures, livestock, cropland, humans, and the natural environment for the years 1866, 1937 and 2023. The aim of the study is to calculate how much nitrogen was being removed from the soil in the form of crops and grazing, and how much was being returned to the soil, giving a soil “balance”.

The results of the study show a large soil nitrogen surplus in 2023, a slightly positive balance for 1937, and a soil nitrogen deficit in 1866. Once nitrogen losses from the soil are taken into account, these results indicate that farmland was being depleted of nitrogen in both 1866 and in 1937, though to a lesser extent in 1937. The reduction in nitrogen depletion is likely thanks to intensive crop rotations with leguminous crops.

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