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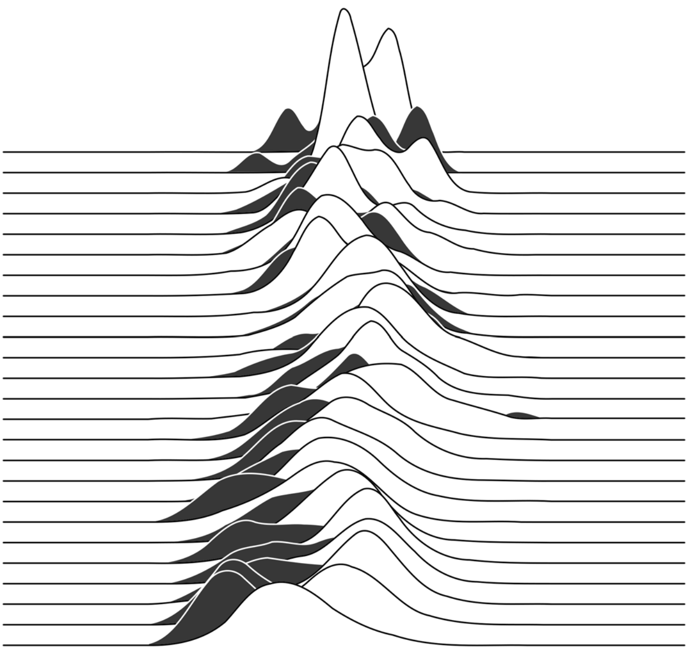
Livestock as resource users and landscape managers

A food systems perspective

Johan O. Karlsson



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Livestock as resource users and landscape managers

Abstract

The role of livestock in sustainable food systems has been questioned due to their large environmental impacts and due to food-feed competition from using feeds that are more efficiently used directly for food. However, livestock can contribute to food system sustainability by using resources otherwise unavailable for food production, such as grass and food processing by-products ('leftover resources'), and by managing agricultural landscapes that promote ecosystem services through *e.g.* grazing semi-natural grasslands or facilitating soil fertility-building crop rotations. These positive contributions of livestock are explored within this thesis. The results showed that in scenarios with livestock limited to leftover resources in an organic and regionalised Nordic food system (FND scenarios), the Nordic land base could provide food for 9–30% more people than the projected 2030 population, despite lower yields and large areas of cropland devoted to fertility-building grass-legume leys. Scenarios of reduced food-feed competition from ceased soybean feed imports into the European Union (EU-S scenarios) showed that cropland demand in deforestation-prone countries in South America decreased by 9–12 Mha, but also that cropland demand in Southeast Asia may increase (0–2 Mha) as palm oil replaces soybean oil. Animal-source food was reduced by 48–75% (FND) and 17–24% (EU-S) in terms of edible protein, and in both sets of scenarios ruminants were favoured over pigs and poultry when optimising for food output, as they utilise grass and other roughages unavailable for other animals. Large areas of cropland devoted to grass-legume leys in the organic FND scenarios showed the importance of accounting for 'cropping system leftovers' when assessing potential animal-source food production from leftover resources under reduced reliance on external inputs in agriculture. Analysis of a suite of indicators for non-provisioning ecosystem services across Swedish farms showed that farms specialising in ruminants had more varied landscapes, semi-natural grasslands, small-scale habitats and better crop sequences than nearby farms specialising in crop production, although variation between farms was large. The findings from this work can hopefully guide food system actors in the challenging task of balancing livestock's positive contributions as resource users and landscape managers against the urgent need to reduce their negative impacts.

Keywords: Livestock, Food-feed competition, Food system, Environmental impacts, Modelling, Ecosystem services, Nordic, Europe, Sweden

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Lantbrukets djur som resursutnyttjare och landskapsvårdare

Sammanfattning

Lantbruksdjurens roll i hållbara livsmedelssystem har ifrågasatts på grund av deras stora miljöpåverkan och konkurrensen mellan foder- och livsmedelsproduktion. Djur kan dock bidra till hållbara livsmedelssystem genom att använda resurser som annars inte är tillgängliga för livsmedelsproduktion såsom gräs och biprodukter från livsmedelsförädling, och som landskapsvårdare genom att t.ex. beta naturbetesmarker eller bidra till hållbara växtföljder. Dessa positiva bidrag utforskas i denna avhandling. Resultaten visade att i scenarier där djuren begränsades till foder som inte konkurrerar med annan livsmedelsproduktion i ett ekologiskt och regionaliserat nordiskt livsmedelssystem (FND) kunde det nordiska jordbruket förse 9–30 % fler människor med mat än den beräknade befolkningen 2030. Detta trots lägre skördar och vallodling på stora delar av åkermarken. Scenarier som beskriver en situation där Europeiska Unionen slutat importera sojafoder (EU-S) visade att efterfrågan på odlingsmark i Sydamerika där det idag råder risk för avskogning minskade med 9–12 Mha, men också att efterfrågan på odlingsmark i Sydostasien riskerar öka (0–2 Mha) om palmolja ersätter sojaolja. Tillgången på animaliskt protein minskade med 48–75 % (FND) och 17–24 % (EU-S) och i båda scenarierna gynnades idisslare framför grisar och fjäderfä när produktionen optimerades för att producera så mycket mat som möjligt. FND-scenarierna med ett helt ekologiskt odlingssystem i Norden visade på vikten av att ta hänsyn till den stora mängden biomassa från vall som uppstår i odlingssystem där insatsmedel i jordbruket minimeras. Denna biomassa kan användas för att utfodra idisslare utan att direkt konkurrera med annan livsmedelsproduktion. En analys av en rad indikatorer för ekosystemtjänster på svenska gårdar visade att gårdar som specialiserat sig på mjölk-, nöt- och fårproduktion hade mer varierande landskap, naturbetesmarker och småbiotoper samt bättre växtföljder jämfört med närliggande gårdar som specialiserat sig på växtodling, men variationen mellan enskilda gårdar var stor. Resultaten från detta arbete kan förhoppningsvis vägleda aktörer inom livsmedelssystemet i den utmanande uppgiften att balansera animalieproduktionens positiva bidrag som resursutnyttjare och landskapsvårdare mot det brådskande behovet av att minska dess negativa effekter.

Nyckelord: Animalieproduktion, Mat-foder konkurrens, Livsmedelssystem, Miljöpåverkan, Modellering, Ekosystemtjänster, Norden, Europa, Sverige

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Dedication

To my daughter Iris
for providing perspective

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Karlsson, J.O., Carlsson, G., Lindberg, M., Sjunnestrand, T. & Röös, E. (2018). Designing a future food vision for the Nordics through a participatory modeling approach. *Agronomy for Sustainable Development* 38, 59.

II. Karlsson, J.O. & Röös, E. (2019). Resource-efficient use of land and animals—Environmental impacts of food systems based on organic cropping and avoided food-feed competition. *Land Use Policy* 85, 63-72.

III. Karlsson, J.O., Parodi, A., van Zanten, H.H.E., Hansson, P.-A. & Röös, E. (2020). Halting European Union soybean feed imports favours ruminants over pigs and poultry. *Nature Food* 2, 38-46.

IV. Karlsson, J.O., Tidåker P. & Röös E. (2022). Smaller farm size and ruminant animals are associated with increased supply of non-provisioning ecosystem services. *AMBIO (manuscript accepted for publication)*.

 Electronic supplementary materials for Papers II and III can be found online and supplementary materials for Paper IV can be provided upon request.

The contribution of Johan O. Karlsson to the papers included in this thesis was as follows:

I. Helped plan the participatory process. Updated and further developed the food system model, collected data, and performed the analysis. Wrote the paper with input from the co-authors.

II. Further developed the food system model, collected data, and performed the analysis. Wrote the paper with input from the co-authors.

III. Conceived the study together with the co-authors. Developed the food system model, collected data, and performed the analysis. Wrote the paper with input from the co-authors.

IV. Conceived the study together with the co-authors. Developed computer algorithms, collected data, and performed the analysis. Wrote the paper with input from the co-authors.

Abbreviations and clarifications

ASF	Animal-source food
CO_2e	Carbon dioxide equivalents (generally calculated using global warming potential over a 100-year timeframe)
Ecosystem service	Any service or benefit (material or non-material) humanity obtains from functioning ecosystems, including ecosystems with a strong human influence such as agro-ecosystems
EU	European Union
EU-S	EU without soybean feed imports (a set of scenarios presented in **Paper III**)
FND	Future Nordic Diets (a set of scenarios presented in **Papers I and II**)
GHG	Greenhouse gas
ha	Hectares (10,000 m^2)
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
Ley	Grass and/or legumes grown on arable land and used for hay, silage or grazing. Leys are often part of a rotation with other crops, but may be more or less permanent.
Livestock	Domesticated animals kept for the provisioning of food

LSD	Livestock density (livestock units per hectare total agricultural land)
LSU	Livestock units
NGO	Non-government organisation
Semi-natural grasslands	Used in this thesis to refer to all pastures and meadows on non-arable land, as opposed to pastures and meadows on arable land, which are referred to as leys
t	Metric tonnes (1,000 kg)

1. Introduction

Keeping domesticated animals for the provisioning of food dates back around 10,000 years (Emanuelsson *et al.* 2009; Hartung 2013) and has been an integral part of human societies since then. In pre-industrial agriculture, livestock were mainly kept outdoors foraging on fallows and meadows and in forest, and were important in transferring nutrients to arable fields (Hartung 2013). The mechanisation of agriculture and large scale adoption of synthetic fertilisers in the second half of the 20th century, together with increased international trade in agricultural commodities, has changed this in many parts of the world, including Europe, and livestock and crop production have become increasingly specialised and geographically separated (Peyraud *et al.* 2014; de Roest *et al.* 2018). Contemporary livestock production is driven by demand for animal-source foods, which has increased rapidly in recent decades. Per-capita meat supply has doubled globally, from 23 kg year^{-1} in 1961 to 44 kg year^{-1} in 2019, and total global supply has increased more than four-fold during the same period (FAO 2022). If no action is taken to curb demand, these trends are expected to continue into the future as an effect of population growth and increasing wealth, albeit at a slower rate, with an expected 38% increase in global demand for animal protein in 2050 compared with 2020 (Komarek *et al.* 2021).

Livestock production now uses around half of the world's agricultural land and 40% of its arable land for feed production and grazing (Mottet *et al.* 2017). A large proportion of the macro- and micronutrients present in feed biomass is not retained in the animal-source foods produced, but lost through metabolic processes in the animals. Around 60% of energy and half of protein present in human-edible feed crops are lost this way globally (Ritchie *et al.* 2018). Livestock are thereby a net sink for several macro- and micronutrients and compete with direct food production for arable land.

Diverting human-edible crops from livestock feeding to direct food uses could enable more food to be produced from existing croplands to feed a growing population (Foley *et al.* 2011; Cassidy *et al.* 2013). However, when livestock use non-human-edible resources and biomass from land where plant-source food production is unfeasible (referred to as 'livestock on leftovers' within this thesis; Garnett 2015), they can contribute to nutrition without food-feed competition and thereby reduce total cropland demand (Van Zanten *et al.* 2018).

Environmental impacts caused by livestock production are another cause for concern. Globally, livestock are estimated to cause at least 16.5% of anthropogenic greenhouse gas (GHG) emissions (Twine 2021), 39% of nitrate released to water bodies and 60% of atmospheric ammonia emissions (Uwizeye *et al.* 2020), causing acidification and eutrophication and forming harmful particulate matter in the atmosphere. Livestock production is also a major driver of tropical forest loss, with negative implications for biodiversity conservation and GHG emissions. Between 2005 and 2013, pasture expansion and soybean production (the vast majority used for animal feed) together accounted for some 47% of tropical deforestation (2.2 and 0.4 Mha year^{-1}, respectively) attributed to agriculture and forestry (Pendrill *et al.* 2019a).

In light of the inefficient use of resources by livestock and their large environmental footprint, their place in future sustainable food systems has been questioned. Modelling studies have shown that global adoption of more plant-based diets, with only moderate inclusion of animal-source foods, is likely to be instrumental in keeping human society within planetary boundaries (Willett *et al.* 2019) and delivering on climate targets (Bajželj *et al.* 2014; Clark *et al.* 2020). At the same time, livestock are considered integral to many farming systems, particularly organic farming (Watson *et al.* 2002; Barbieri *et al.* 2021), in which they make use of and recirculate nutrients from leys and pastures. Ruminant livestock are also important landscape managers, having given rise over time to *e.g.* semi-natural grasslands with high levels of biodiversity (Emanuelsson *et al.* 2009), delivering multiple ecosystem services to society (Bengtsson *et al.* 2019). By utilising forage crops, livestock production can also incentivise crop rotations that benefit pest and weed regulation, as well as nitrogen fixation (Albizua *et al.* 2015; Martin *et al.* 2020).

This thesis contributes to the growing field of research on the role of 'livestock on leftovers' in sustainable food systems (see Van Zanten *et al.* (2018) for a review). Specifically, it furthers the conceptual understanding of resources that can qualify as leftovers available for animal feeding without causing food-feed competition, especially in the context of farming systems relying more on ecosystem services for nutrient supply and crop disease, pest and weed protection. It also takes a broad food systems approach by accounting for the effects of limiting food-feed competition on optimal animal production systems for maximising food supply, environmental impacts and human nutrition. Finally, it provides new insights into how agricultural landscapes and associated ecosystem services differ between farms specialising in crop production and different animal production systems, and connects the partly overlapping and partly diverging roles of livestock as resource users and landscape managers.

2. Aim and structure

2.1 Aim

The overarching aim in this work was to provide a better understanding of: (1) the role of livestock in upcycling leftover resources to nutritious food and the food system-level consequences of reducing the use of food-competing feeds, and (2) the role of livestock in shaping agricultural landscapes and associated supply of ecosystem services. This aim was achieved by pursuing four specific objectives, which were to:

i. Further develop the 'livestock on leftovers' concept, especially in relation to organic cropping systems.
ii. Develop scenarios for future food systems in which the use of food-competing feeds for livestock production is limited, while food supply is maximised.
iii. Assess the effects of the scenarios developed on (1) the optimal number and species of livestock and associated land use, (2) human diets and nutrition, and (3) environmental impacts.
iv. Develop a suite of indicators for supply of ecosystem services other than the direct provisioning of food, and assess the association between different types of livestock production systems and the ecosystem service indicators.

2.2 Structure of research and thesis

This thesis is based on the work presented in **Papers I-IV,** which is schematically presented in **Figure 1**.

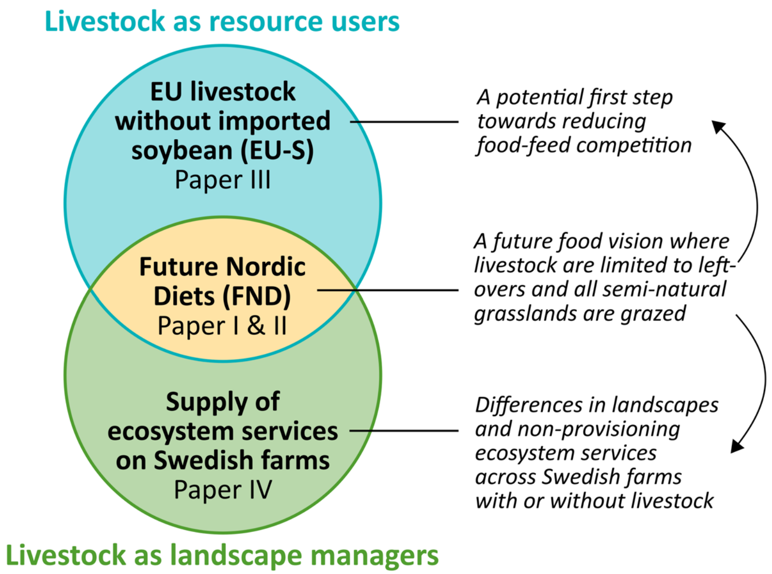

Figure 1. Schematic illustration of the work conducted in Papers I-IV in this thesis.

In **Papers I** and **II**, scenarios for a future Nordic food system based on organic production and livestock on leftovers (Future Nordic Diets (FND) scenarios) were co-developed with a group of Nordic non-government organisations (NGOs). The scenarios were assessed in terms of potential food supply, human nutrition and environmental impacts. These scenarios represented a complete rewiring of the Nordic food system, in line with the NGOs' vision of an organically farmed Nordic region with livestock strictly limited to leftover resources, while all semi-natural grasslands in the Nordic region are managed through grazing to preserve biodiversity and associated supply of ecosystem services. To achieve transition towards such a future food system vision, potential first steps also need to be identified. One such first step is reducing dependency on imported soybean feeds, something that is already on the political agenda in the European Union (EU) due to its association with deforestation and other environmental degradation, as well as the geopolitical risks with heavy reliance on imports for EU food supply. Therefore, in **Paper III**, counterfactual scenarios based on current EU livestock production, but excluding soybean feed imports (EU-S scenarios), were developed and assessed in terms of livestock production potential, nutrition supply and land use impacts.

In **Papers I** and **II**, the role of livestock as landscape managers was accounted for by including maintenance of semi-natural grasslands as a key criterion in the scenarios. However, livestock farming may also affect other aspects of agricultural landscapes and ecosystem services. Therefore, in **Paper IV**, a suite of indicators for non-provisioning ecosystem services was developed and values of these were calculated for a large subset of Swedish farms, to assess supply of ecosystem services across different farm types, with or without livestock and with different livestock species. Such knowledge is important for handling potential trade-offs between environmental impacts, food production and other ecosystem services in a transition towards food systems with reduced livestock production in line with a livestock on leftovers approach. **Figure 2** provides an overview of how the two roles of livestock were accounted for in **Papers I-IV**.

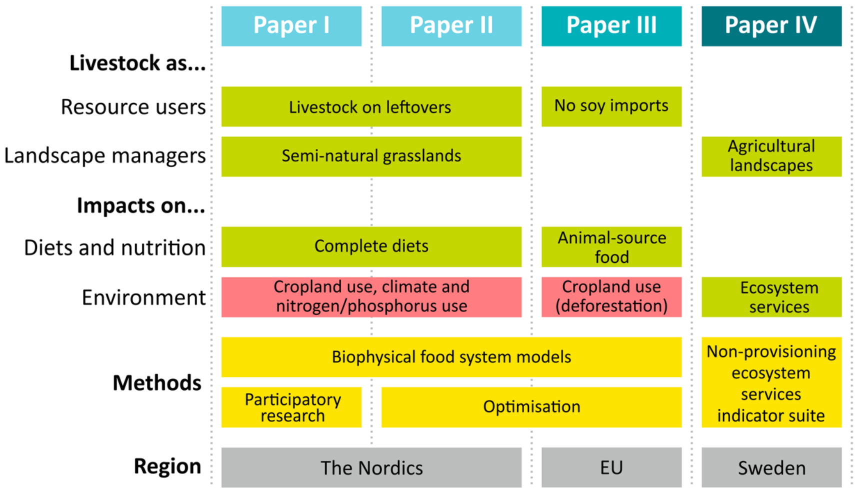

Figure 2. Overview of how the roles of livestock as resource users and landscape managers and the impacts of livestock on diets and nutrition and the environment were included in the papers on which this thesis is based. The methods used are also indicated, as is the geographical region to which the different studies pertain.

Livestock may also play other roles in food systems by *e.g.* providing livelihoods and financial security and being culturally embedded in diets, traditions and tastes. However, these aspects were beyond the scope of this thesis. In addition, a European or even Northern European perspective was applied and conclusions drawn therefore mainly pertain to livestock production and animal-source food consumption in these geographical and socio-economic contexts, although many aspects covered have global relevance.

The remainder of this thesis is structured as follows: A brief background on the roles of livestock in resource use and food-feed competition, diets and nutrition, environmental impacts, supply of ecosystem services and using leftover resources is provided in Chapter 3. The methods used are presented in Chapter 4, including development of the 'livestock on leftovers' concept. In Chapter 5, results are presented and discussed, starting with the FND and EU-S scenarios and their outcomes in terms of agricultural production, diets and nutrition and environmental impacts. This is followed by results from analysing ecosystem services across Swedish farms. Finally, a general discussion is provided in Chapter 6, while the main conclusions from the work are presented in Chapter 7.

3. Background

3.1 Livestock feeding and food-feed competition

Following macro trends in population growth, dietary changes and changing energy systems, competition for agricultural biomass for food, feed and fuel uses is increasing (Muscat *et al.* 2020). Animal feeding can compete with food production both directly, by using *e.g.* cereals and other edible grains for feed, and indirectly, by using land for feed production where plant-source food could instead be produced. The extent to which livestock rely on food-competing feeds varies dramatically across regions and livestock production systems. Mottet *et al.* (2017) estimated that of the six billion tonnes of dry matter feed used by livestock globally, the majority (73%) is in different forms of roughages (*e.g.* grass and crop residues), 5% comprises oilseed meals, 8% other by-products and wastes, and only 14% consists of grains and other feeds directly edible to humans. Nonetheless, redirecting major staple crops towards direct human consumption could increase calorie supply by an estimated 49% (Foley *et al.* 2011). In the EU, the shares of roughages (66%) and by-products other than oilseed meals (3%) are lower than the global average, while the shares of grains (21%) and oilseed meals (10%) are higher (aan den Toorn *et al.* 2020). Conversely, in lower-income countries the share of roughages in animal feed is generally higher and the share of human-edible feeds lower (Mottet *et al.* 2017).

Apart from the regional differences, there are also large differences across livestock species and production systems. Compared with monogastric animals, ruminants generally need more feed per kg human-edible protein produced. However, higher inclusion of roughages and other inedible feeds generally leads to lower use of food-competing feeds per kg human-edible protein produced in ruminant systems compared with monogastric systems (Mottet *et al.* 2017).

Different forms of roughages are important feed sources globally and in the EU, where they account for more than 40% of crude protein in feeds (European Commission 2019). While the opportunity to use these feeds directly as food is very limited, their use may still contribute to food-feed competition through land occupation. In the EU, 20% of arable land is used for temporary grasslands and other fodder crops[1] and some land currently in permanent grassland may potentially be converted to arable land. On a global level, Mottet *et al.* (2017) estimated that around one-third of grassland currently used by livestock has non-marginal plant-source food production potential.

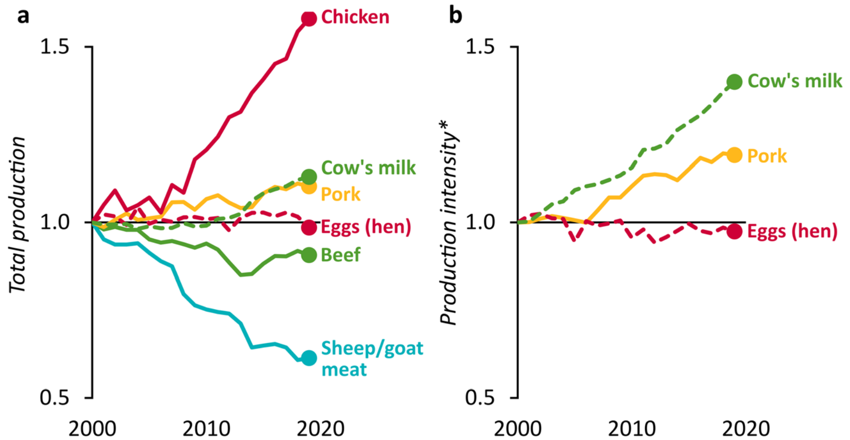

Figure 3. a) Yearly production of meat, milk and eggs in the European Union normalised to production in the year 2000. **b)** Production intensity* in the European Union normalised to intensity in the year 2000. *Intensity is expressed in terms of yearly milk production per dairy cow for cow's milk, yearly egg production per laying hen for eggs, and yearly pork production per total number of pigs for pork. Source: FAOSTAT (FAO 2022).

As indicated previously, oilseed meal, which is the protein-rich fraction of oilseeds remaining after oil extraction, is another important feed source globally and even more so in the EU. Most types of oilseed meals are considered inedible by-products of vegetable oil production (although food uses of *e.g.* rapeseed meal are being explored; Östbring *et al.* 2020), and can

[1]Temporary grasses and grazings + green maize + legumes and other crops harvested green, divided by total arable land in 2014-2016 according to Eurostat data (European Commission 2022)

be considered not to compete with food production. The exception is soybean, where demand for the protein meal is more important than that of the oil in driving cropland demand for soybean production (Schmidt 2015). Moreover, soybean meal can be processed into soy flour used in *e.g.* many meat and dairy substitutes. Therefore, the use of soybean meal in animal feed competes with food production both directly through a missed opportunity to use it in the food industry and indirectly through its cropland demand.

While less intensive production systems, where feed requirements are lower, and ruminant systems tend to use less food-competing feed per kg human-edible protein produced (Wilkinson 2011; Mottet *et al.* 2017), the trend in the EU is rather towards an increased focus on monogastric animals and intensified production systems. From 2000 to 2019, production of poultry meat in the EU grew by almost 60%, while ruminant meat production decreased (**Figure 3a**). During the same period, milk yield per cow increased steadily, as did total pork production in relation to the total number of pigs kept (**Figure 3b**). For dairy cows, increased production intensity often necessitates supplementation of grass with other feeds to meet the higher requirements (van den Pol *et al.* 2008), which may increase the share of food-competing feeds in ruminant diets. Overall, these trends point towards increased food-feed competition in EU livestock production.

3.2 Animal-source foods in diets and nutrition

Animal-source foods make a vital contribution to diets globally, with terrestrial livestock products supplying 17%, 33% and 43% of global intake of calories, protein and fat, respectively, according to FAO Food Balance Sheets (FAO 2022). In Europe the shares are higher, with 28% of calories and 52% of protein and fat supplied from terrestrial livestock products. The contribution from aquatic animal products is comparatively smaller, comprising around 7% of protein and 2% of fat consumed globally and in the EU. Animal-source foods also supply several micronutrients, some of which can be difficult to consume in sufficiently high quantities in a completely plant-based diet (Murphy & Allen 2003). In particular, vitamins A and B_{12} and riboflavin, as well as calcium, iron and zinc, have been found to be low in exclusively plant-based diets (Murphy & Allen 2003).

Table 1. *Share of global intake in the form of animal-source food for different macronutrients, minerals and vitamins. Arrows indicate whether livestock are a net source (↑) or sink (↓) for that nutrient on a global level. The comments highlight some relevant aspects and nutrition status in Europe*

Nutrient	ASF[1]	↑/↓	Comments
Macronutrients			
Calories	18%	↓	
Digestible protein	47%	↓	
Fat	36%	↑	Total fat and saturated fats consumed above recommended levels in many European countries[2]
Minerals			
Calcium	30%	↓	
Iron	10%	↓	The most common micronutrient deficiency globally[3]. Low attainment for young women in Europe[2]
Zinc	30%	↓	No concern in Europe[2]
Vitamins			
Vitamin A	28%	↑	Vitamin A deficiency is a leading cause of childhood morbidity and mortality in low-income countries[3]. Average intakes in European countries generally meet recommendations[4]
Vitamin B_6	22%	↓	
Vitamin B_{12}	100%	↑	Only found in animal products. Of limited concern in Europe[2]
Vitamin D	?	?	Mainly supplied through UVB light exposure. Dietary sources include fatty fish and fortification. High prevalence of vitamin D insufficiency in Europe and the rest of the world[5]
Riboflavin	~50%[6]	?	Milk and dairy are the main source of riboflavin in high-income settings and low dairy consumption may lead to deficiencies[7].
Folate	8%	↓	Low attainment in Europe[2]

[1]Contribution of animal-source foods (ASF) to intake globally. Caculated from data in Ritchie *et al.* (2018). The values for macronutrients differ from those derived directly from the FAO Food Balance Sheets as Ritchie et al. (2018) account for consumption-level food waste and protein digestibility.

[2]Rippin *et al.* (2017).
[3]Bailey *et al.* (2015).
[4]Efsa Panel on Dietetic Products and Allergies (2015).
[5]Calvo *et al.* (2005).
[6]Approximated based on Swedish (Amcoff *et al.* 2012), Italian (Sette *et al.* 2013) and Dutch (Van Rossum *et al.* 2011) data.
[7]Powers (2003).

On the other hand, animal-source foods are also often rich in in cholesterol and saturated fats, which are risk factors for *e.g.* heart disease (Rohrmann *et al.* 2013). Large cohort studies controlling for other major lifestyle risk factors have associated red and processed meat intake with increased all-cause mortality risk (Pan *et al.* 2012; Rohrmann *et al.* 2013). **Table 1** shows the contribution of animal-source food to global supply of selected macro- and micronutrients with relevance for nutrition, particularly under reduced animal-source food consumption.

3.3 Environmental impacts of livestock production

Livestock production contributes to environmental impacts both directly, through *e.g.* emissions from animals, manure management and housing, and indirectly, through impacts arising in feed production and associated land use and land use changes.

In ruminant systems, enteric fermentation in the rumen causing methane emissions is the single largest contributor to climate impacts, while in monogastric systems the production of feeds and associated land use changes are generally responsible for the majority of climate impacts (Gerber *et al.* 2013; Poore & Nemecek 2018). For other impact categories such as eutrophication and acidification, the production of feeds contributes relatively more to total lifecycle impacts for both ruminant and monogastric systems, but directly livestock-related emissions from *e.g.* manure management also play a significant role (Poore & Nemecek 2018).

In the EU, livestock production is estimated to contribute 76% of terrestrial biodiversity loss, 81% of GHG emissions and 73% of nitrogen and phosphorus leaching to water bodies, out of the total impacts of EU agricultural production (Leip *et al.* 2015).

While many of the impacts associated with EU livestock production occur within the EU, some originate in other regions of the world due to feed imports. International trade in agricultural commodities is a leading cause of deforestation globally, with negative impacts on biodiversity (Chaudhary & Kastner 2016) and GHG emissions (Pendrill *et al.* 2019b). Leip *et al.* (2015) attributed almost half of GHG emissions related to EU livestock to feed imports, mainly due to soybean imports and its contribution to deforestation.

3.4 Livestock, landscapes and ecosystem services

In addition to supplying animal-source food, livestock production may also provide other benefits to society through different non-provisioning ecosystem services that arise in agricultural landscapes as a direct or indirect consequence of livestock farming. In many parts of Europe, semi-natural grasslands have developed over centuries from livestock keeping and associated haymaking and grazing by cattle and sheep (Emanuelsson *et al.* 2009). These areas are often very biodiverse (Pärtel *et al.* 2005; Emanuelsson *et al.* 2009) and associated with a number of ecosystem services, including providing habitats for pollinating insects (Öckinger & Smith 2007) and predatory insects (Bianchi *et al.* 2006; Alignier *et al.* 2014) that benefit crop production. They have also been associated with non-material services related to recreation and cultural heritage (Lindborg *et al.* 2008; Marzetti *et al.* 2011; Bengtsson *et al.* 2019). Furthermore, the presence of livestock in a landscape has been shown to positively affect landscape aesthetics (Kumm 2017; Serrano-Montes *et al.* 2019).

Ruminant livestock production may also provide incentives for incorporating perennial forage crops into arable crop rotations, which has beneficial effects on soil structure and carbon sequestration, crop protection and nitrogen fixation, which may thus reduce the need for external inputs in the form of chemical crop protection and fertilisers (Albizua *et al.* 2015; Martin *et al.* 2020).

While these services can all be linked to livestock production, this does not mean that all livestock production contributes equally. Nonetheless, when considering reduced animal-source food consumption as a strategy to reduce resource use and environmental impacts of food systems, an associated reduction in the number of grazing animals could lead to a diminished supply of many ecosystem services from European agricultural landscapes (Ford *et al.* 2012; Bengtsson *et al.* 2019; Johansen *et al.* 2019). This represents a potential goal conflict that needs to be managed.

3.5 Livestock on leftovers

The livestock on leftovers concept has been explored in several publications, under different labels such as ‘livestock on ecological leftovers’ (Garnett 2009), ‘default livestock’ (Fairlie & Logsdon 2010), ‘the consistency strategy’ (Schader *et al.* 2015) and ‘low-cost livestock’ (Van Zanten *et al.*

2018). In all these, livestock are seen as a means to utilise resources otherwise unavailable for food production for producing nutritious food, rather than to supply an exogenous demand for meat, milk and eggs. This means that diets and animal-source food consumption need to align with the availability of leftover resources, which in effect caps animal-source food consumption at a certain level.

One of the earliest publications on the concept, by Elferink *et al.* (2008), showed that pigs fed predominantly on low-value residual biomass have a small environmental footprint, if impacts incurred in the production of residual feeds are allocated to the process generating the residues, rather than to pork production. As the availability of residues is constrained by definition, this only allows for a certain level of pork production, beyond which additional feeds such as cereals or other grains that compete with direct food uses would be needed, thus increasing the environmental footprint per unit of pork produced.

The concept has since been further explored in studies modelling different scenarios where livestock are limited to leftover resources at country (Röös *et al.* 2016; Van Kernebeek *et al.* 2016), region (Röös *et al.* 2017a) or global level (Schader *et al.* 2015; van Zanten *et al.* 2016a; Röös *et al.* 2017b). A review by Van Zanten *et al.* (2018) concluded that livestock limited to leftovers could supply 9-23 g protein per capita and day to diets globally. This would mean reduced animal-source food consumption in some regions (*e.g.* in the EU, where current supply of protein from terrestrial livestock products is above 50 g cap^{-1} day^{-1}; FAO 2022), while allowing for increased consumption in regions where animal-source food consumption is currently low. The livestock on leftovers concept has also been explored in conjunction with organic agriculture, where it has been shown that scenarios with a large share of organic farming are only feasible with simultaneous reductions in the use of food-competing feeds (Muller *et al.* 2017). The livestock on leftovers concept has several commonalities with the concept of agroecology. While agroecology is not clearly defined (Wezel *et al.* 2009), animal production systems less dependent on concentrates that make use of grasslands are often emphasised. The scenario of an agroecological food system in Europe presented by Poux and Aubert (2018) also aligns well with scenarios of livestock on leftovers in terms of protein supplied from livestock products (24 g cap^{-1} day^{-1}).

Most livestock on leftovers scenarios involve a strong reduction in consumption of meat from pigs and poultry, while ruminant milk and meat production is less affected (Van Zanten *et al.* 2018). This was confirmed by van Hal *et al.* (2019), who used an optimisation algorithm to maximise animal protein output based on available leftover resources in the EU. Their results showed that milk and beef production, together with reduced production of pig meat in low-intensity systems, resulted in the most efficient conversion of leftover resources to human-edible protein.

4. Methods and concept development

The following chapter provides an overview of the methods used in **Papers I-IV**. First, a definition of leftover resources developed in **Paper II** is provided (section 4.1), followed by descriptions of the FND (**Papers I** and **II**) and EU-S (**Paper III**) scenarios and how they were modelled (section 4.2). Finally, the methods used to assess ecosystem services on Swedish farms in **Paper IV** are presented (section 4.3).

4.1 Defining leftover resources

In **Paper II,** a nomenclature for leftover resources was proposed, subdividing them into *land use leftovers*, *cropping system leftovers* and *by-products and wastes*. **Table 2** summarises these three leftover resources and provides examples of feeds that may qualify. The following sections elaborate on criteria needed for a certain resource to qualify as a leftover, by referring to the literature and to work contained within this thesis.

4.1.1 Land use leftovers

Land use leftovers refer to biomass from land with no alternative use for food production. Such areas include grasslands and other grazing lands (*e.g.* forest or alpine pastures), where soils, morphology or location make cropping unfeasible. This leftover resource is generally assumed to equate to current grassland areas (*e.g.* Schader *et al.* 2015; Röös *et al.* 2017b; van Hal *et al.* 2019). However, Mottet *et al.* (2017) estimated that around one-third of grassland areas currently used for livestock are potentially convertible to cropland. Defining land areas that can be considered land use leftovers is thus not entirely straightforward and assumptions around this may dramatically affect results in terms of how much animal-source food can be produced without competing with plant-source food production.

In the FND scenarios (**Papers I** and **II**), a stricter definition was used where land use leftovers were assumed to comprise semi-natural grasslands as well as forest and alpine pastures in Norway, thereby excluding more intensively managed permanent grasslands where cultivation of arable crops is possible. This decision was based on the benefits provided by grazing livestock in these areas for biodiversity conservation and related ecosystem services in line with Röös *et al.* (2016).

Depending on region and livestock production system, the potential to utilise land use leftovers without causing food-feed competition may also be constrained by the availability of other feed sources. For example, the potential to use pasture resources may be constrained by the availability of leftover feeds outside the grazing season.

It should also be noted that while land use leftovers are considered unavailable for direct plant-source food production, other uses such as for bioenergy, forestry or nature conservation are often possible.

4.1.2 Cropping system leftovers

Cropping system leftovers refer to inedible break, cover or inter- crops introduced in arable crop rotations to benefit the cropping system by *e.g.* supplying nitrogen, sequestering carbon, improving soil structure and preventing pests and weeds. A notable example is crop rotations including leguminous forage crops such as clover or alfalfa, which are often a necessity in organic farming, but may also benefit conventional cropping systems by *e.g.* promoting soil microbiology and reducing fertiliser needs (Nevens & Reheul 2002; Albizua *et al.* 2015). On stockless organic farms, the biomass of such crops is generally ploughed under *in situ*, but may be ensiled or anaerobically digested for storage and improved timing of nitrogen addition to subsequent crops (Råberg *et al.* 2018; Koppelmäki *et al.* 2019). In either case, such practices exclude land from food production if the biomass is not used in livestock feeding, thus making it a leftover resource that is not in competition with direct food crop production.

The concept of cropping system leftovers was first introduced in **Paper II** and had not previously been explicitly covered in the 'livestock on leftovers' literature. For example, in their global scenarios for organic farming in combination with reduced food-feed competition, Muller *et al.*

(2017) assumed that increased inclusion of leguminous crops in rotations would follow current shares of different legume crops, which thereby *"over-estimates the relative share of food legumes with respect to green manure"* (Muller *et al.* 2017, p. 8) and consequently under-estimates the availability of cropping system leftovers.

Similarly to land use leftovers, cropping system leftovers may have other non-food uses, such as for bioenergy production.

4.1.3 By-products and wastes

By-products and wastes refer to biomass generated in the production of plant- or animal-source food but not edible for humans or desired for direct human consumption. This may include crop residues, low-grade crops, by-products of food processing such as bran, peel, oilseed cake/meal, sugar or ethanol processing by-products, or different forms of food waste and losses such as bakery waste.

The amount of by-products and wastes that can be considered leftovers available for livestock feeding depends on assumptions regarding what is edible and desired for human consumption. For example, by-products from milling of wheat and other cereals (*e.g.* bran) are a major feed commodity worldwide, but their generation depends entirely on the quality sought in the final grain product destined for human consumption. The whole grain can be used for food, but normal grain-to-flour extraction rates in wheat mills are in the order of 75-80% (Heuzé *et al.* 2015). Assumptions on the plant-based part of human diets are therefore important to assess the potential availability of by-products and wastes available for livestock. For example, using current diets or trajectories would generate more leftovers in the form of *e.g.* milling and sugar processing by-products than assuming healthy diets with an increased share of whole grains and reduced consumption of refined sugars (as suggested by *e.g.* Willett *et al.* 2019). This effect was documented by van Selm *et al.* (2022), who found that more whole grains in diets reduced the potential to produce poultry meat and eggs based on leftover resources compared with scenarios with more refined grains.

4.2 Scenario development

This section describes how the FND and EU-S scenarios were developed. The FND scenarios, which are presented in **Papers I** and **II**, describe a

Nordic food system in 2030 where the majority of food consumed is produced within the Nordic countries of Denmark, Finland, Norway and Sweden under organic agriculture and livestock on leftovers. The EU-S scenarios, presented in **Paper III**, show potential EU livestock production without imported soybean feed (a potential first step to reducing food-feed competition) and without feed production encroaching on cropland currently used for other purposes.

4.2.1 FND: Future Nordic Diets

The FND scenarios (**Papers I** and **II**) were developed using a participatory approach where a group of Nordic NGOs were responsible for making the main normative decisions underlying the scenarios, and researchers were responsible for translating these normative decisions to quantitative model inputs (**Paper I**). The main normative decisions resulting from this process were that:

- i) Diets should be based on foods currently consumed in the region and seek to fulfil Nordic nutrient recommendations.
- ii) The majority of food should be produced within the Nordic region.
- iii) Food should be produced in an organic farming system.
- iv) Arable land on peat soils should be re-wetted and 15% of Danish arable land should be set aside for nature conservation.
- v) Food waste should be reduced.
- vi) Livestock should only be fed on leftover resources and should not compete with food production for arable land.
- vii) Semi-natural grasslands in the Nordic region should be grazed.
- viii) Agriculture should be self-sufficient in renewable energy by using some leftovers for bioenergy production.
- ix) The Nordic region should supply food for as many people as possible within set constraints.

A healthy baseline diet developed by the Swedish National Food Agency that resembles current eating patterns and fulfils Nordic nutrition recommendations (Enghardt-Barbieri & Lindvall 2003) was used as a starting point for the scenarios. This diet was then translated into food commodities that needed to be produced, taking account of point (ii) above by *e.g*. assuming 'fruit juice' to be produced from apples, replacing rice with other cereals, and focusing on vegetables that can be grown in open fields in the Nordic climate. To account for point (iii) above, all annual crops were assumed to be grown in a crop rotation that included on average at least one-third grass-legume ley cultivation.

Following from point (vi) above, all animal-source food in the baseline diet was excluded and replaced with animal-source food produced from livestock limited to leftovers under two different scenarios that reflected different views on the role of ruminants and how to use leftovers in the future Nordic food system. In the first scenario (Sufficiency, SY), the need to curb GHG emissions through a reduced ruminant herd, while at the same time meeting nature conservation goals in terms of preserving semi-natural grasslands, was acknowledged. Ruminant livestock were therefore limited to the minimum number required to graze all semi-natural grasslands. In this scenario, land use leftovers in the form of semi-natural grasslands and all applicable by-products and wastes were used to feed livestock, while cropping system leftovers in the form of ley biomass were only partially utilised. In the second scenario (Efficiency, EY), the role of ruminants in upcycling leftover resources was acknowledged and their numbers were allowed to increase to utilise all leftovers generated in the system. **Figure 4** and paragraphs A-D below describe how land and leftovers were allocated to different uses in the scenarios:

A. All semi-natural grassland (**Figure 4**, **A1**) was grazed by ruminant livestock in both scenarios. In the EY scenario, ruminants were also allowed to graze Norwegian alpine and forest pastures, as long as this increased the number of people it was possible to feed in the scenario (**Figure 4**, **A2**).
B. Cropland was allocated to produce all plant-source food in the baseline diet (**Figure 4**, **B1**) and additional cereals, pulses and rapeseed to compensate for reduced animal-source food consumption (**Figure 4**, **B2**). The plant-source food production generated by-products and wastes used to supplement ruminant diets and feed monogastrics (**Table 2**). Food waste, straw and manure were used for bioenergy production to provide electricity and heat animal houses, grain dryers, greenhouses and aquaculture tanks and to power agricultural machinery.

C. Ley was grown on one-third of all arable land to ensure feasible organic crop rotations. In the SY scenario, this biomass was partially used to feed dairy cows and provide winter feed for other ruminants (**Figure 4**, **C1**) and, if needed, to produce bioenergy (**Figure 4**, **C2**). The remaining ley was left in the field as green manure in the SY scenario. In the EY scenario, this biomass was used to support a larger ruminant herd (**Figure 4**, **C3**).

D. Additional ley was introduced on arable land if the frequency of pulses or rapeseed exceeded limits set to ensure crop rotations that limit the occurrence of plant diseases and weeds in the organic cropping system. This area was left as green manure in the SY scenario and used to feed ruminants in the EY scenario (**Figure 4**, **D1**). In the EY scenario, the introduction of feed grains for monogastric animals was also permitted, as long as it increased the number of people possible to feed (**Figure 4**, **D2**).

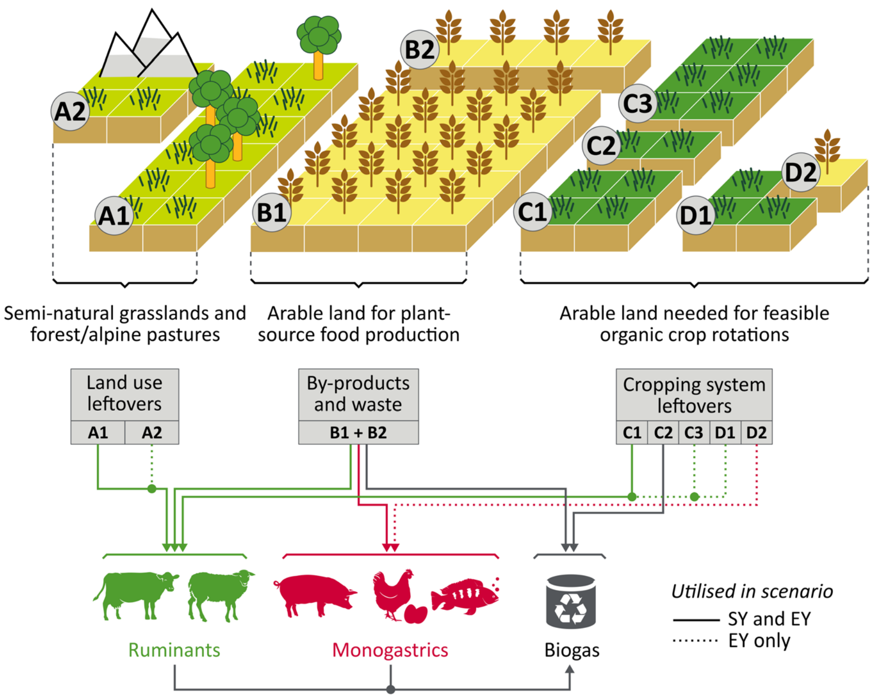

Figure 4. Schematic illustration of how land and leftovers were used in the Future Nordic Diets (FND) scenarios. SY = Sufficiency, EY = Efficiency.

Table 2. *Leftover resources available for livestock production without competing with plant-source food production. Leftovers used in the Future Nordic Diets (FND) scenarios are also indicated*

Leftover	Feed example(s)	Used in FND scenarios	
		SY	EY
Land use leftovers			
Land w/o food crop production potential	Permanent/semi-natural grasslands	Yes	
	Forest/alpine pastures	No	Yes (Norway)
Cropping system leftovers			
Inedible break crops	Grass/clover leys for grazing or hay/silage	In part	Yes
Cover crops	Brassica, legumes *etc.* used for grazing or silage	No	
By-products and wastes			
Low grade crops	Grains not meeting quality standards	No	
	Low-grade roots and vegetables	Yes (potatoes and roots)	
Crop residues	Straw	Yes (for bedding and bioenergy)	
	Stover	No	
Plant processing by-products	Oilseed meals/cakes	Yes (rapeseed cake)	
	Sugar processing by-products	Yes	
	Cereal husks/bran	Yes	
	Brewery/distillation by-products	Yes	
Animal processing by-products	Whey	No (used for food)	
	Fish meal from fish discards/waste	Yes	
Bioenergy by-products	Bioethanol distillation by-products	n/a	
Food waste	Bakery waste	Yes	
	Swill	No (against regulations)	

Five livestock species (cattle, sheep, pigs, poultry and Nile tilapia aquaculture) were included in the scenarios. Cattle were assumed to be kept in low-yielding dairy systems (reflecting a presumed need for more durable breeds), with young animals (heifers and steers) grazing semi-natural grasslands to a large extent. Sheep were assumed to be kept in extensive systems with lambs reared on pastures during summer and slaughtered before moving the ewes indoors for winter. The number of sheep was connected to the number of cattle, such that the proportions of cattle and sheep meat in the diets reflected current consumption in the Nordic countries, except in the EY scenario where the number of sheep in Norway was allowed to increase to make better use of alpine pastures. The pig production systems were designed to reflect organic practices and pigs were assumed to be kept on ley pastures on arable land during summer. For poultry, a dual-purpose system was used, with poultry meat produced from culled laying hens and cockerels (Leenstra *et al.* 2010). Aquaculture was in land-based systems with Nile tilapia, as such systems are better adapted for utilising plant-based feeds compared with other aquaculture systems (Goda *et al.* 2007).

A non-linear optimisation algorithm was used to find the number of different livestock species and allocation of feed resources between species that maximised total food output in terms of the number of complete diets possible to provide from Nordic land resources (see section 4.2.3).

4.2.2 EU-S: EU livestock without imported soybean

While the FND scenarios represented complete adherence to the livestock on leftovers concept, radically changing the food system and agricultural practices, the EU-S scenarios (**Paper III**) were designed to represent a potential first step towards a livestock on leftovers future. The EU-S scenarios represented a situation where the EU (including the United Kingdom) does not import any soybean feeds and at the same time does not use more land within the EU for direct feed cultivation than currently used. The case of imported soybean was selected for three principal reasons:

i) Imported soybean feeds are widely used in the EU and account for 27% of total non-roughage feed protein (European Commission 2019).

ii) Soybean has high potential for direct food use in *e.g.* meat and dairy substitutes, where it provides both highly digestible protein (Rutherfurd *et al.* 2015) and fat and has been associated with health benefits (Anderson *et al.* 1995; Xu *et al.* 2004)

iii) Reducing the EU's soybean import dependency is on the political agenda, due to the association with deforestation (see *e.g.* the European Commission's recent proposal on banning products associated with deforestation on the EU market; European Commission 2021), and due to the geopolitical risks associated with import dependency for a large part of EU animal-source food production (see *e.g.* the European Parliament's strategy for promoting EU protein crops; European Parliament 2018)

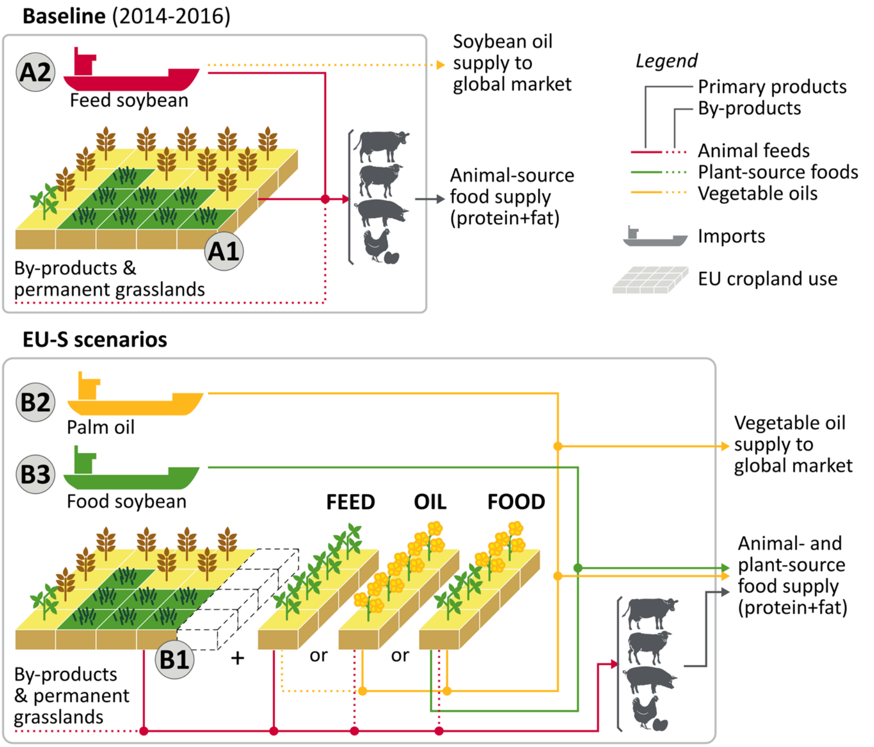

Figure 5. Schematic illustration of European Union (EU) cropland use and imports in the baseline and scenarios for EU livestock without imported soybean (EU-S).

As a starting point for the scenarios, a baseline scenario was established by calculating the total amount of feeds and associated cropland used by EU livestock in 2014-2016 (**Figure 5**, **A1**). These calculations were based on animal production statistics in the FAOSTAT database (FAO 2022) and animal feed rations from the Common Agricultural Policy Regionalised Impact (CAPRI) model version 2.1 (Britz & Witzke 2014).

From the total pool of feed currently used by animals in the EU, all soybean feeds directly imported or produced from imported beans (**Figure 5**, **A2)** were excluded. Livestock production was then optimised in each EU member state by finding the number of different types of animals and feed rations that maximised supply of edible protein in animal-source foods from the pool of available feeds (see section 4.2.3). As soybean feeds are rich in protein, their exclusion resulted in some cereals and other energy-rich feeds remaining unutilised, which made land within the EU where these crops are currently produced available for other purposes (**Figure 5**, **B1**). The use of this freed land was considered under three counterfactual scenarios.

In the first scenario (FEED; S1 in **Paper III**), the freed land was used to increase EU production of pulses and soybean for animal feed, in order to find the maximum animal-source food production potential under ceased soybean imports (and without using more EU cropland for feed production). As the majority of soybean is fed to livestock in the form of soybean meal, reduced use of soybean feeds also resulted in reduced supply of the associated soybean oil, which is currently used for *e.g.* food or bioenergy. In the scenarios, it was assumed that this reduced oil supply would be compensated for by increased production of palm oil (**Figure 5**, **B2**), which is the marginal oil on global vegetable oil markets (Schmidt 2015). As palm oil production is also associated with deforestation (Pendrill *et al.* 2019a), reduced soybean meal use might shift environmental impacts from one product and region to another. Therefore, a second scenario (OIL; S2 in **Paper III**) was considered where the freed land was used to increase EU production of rapeseed oil in order to reduce demand for palm oil production and where the by-product rapeseed meal was used for EU livestock feeding. All scenarios resulted in reduced production of animal-source food, which was compensated for by assuming that soybean and palm oil imports would be needed to fill the protein and fat gap in human diets (**Figure 5**, **B2+B3**). This meant that some of the imported soybean currently used for feed production was needed for plant-source food production in the two first scenarios. A third scenario (FOOD; S3 in **Paper III**) was therefore developed, where the protein gap was instead filled by using the freed land to increase EU production of pulses and soybean for direct human consumption. This did not require all freed land from reduced energy-rich feed production and the remaining land was used to increase rapeseed production, analogously with the OIL scenario.

4.2.3 Optimisation of animal numbers and feed rations

In both the FND and EU-S scenarios, optimisation algorithms were used to determine the number of animals of different types to be included in the scenarios and the distribution of feed resources.

In the FND scenarios, the optimisation problem was solved with Microsoft Excel Solver, using the generalised reduced gradient algorithm (Fylstra *et al.* 1998). The solver was set up to select values for: i) the number of complete diets supplied, ii) the number of animals of each livestock species, iii) livestock feed rations and iv) the area cultivated with ley. The variable to maximise was the number of complete diets supplied. Constraints were introduced to: i) limit land use to available areas of cropland and semi-natural grassland, ii) ensure feed rations met species-specific requirements, iii) ensure crop rotations were suitable for organic farming (*i.e.* at least one-third ley and not too frequent cultivation of rapeseed and grain legumes) and iv) ensure adequate protein and fat supply to human diets. As the optimisation algorithm is sensitive to starting values and cannot guarantee convergence to the global optima, each solution was manually checked to ensure that: i) all available cropland was used, ii) all by-products were used and iii) no animal species was over-supplied with feed energy. If any of these criteria was not met, the starting values were changed and the solver was run again until a solution meeting all three criteria was found. This method ensures a biophysically feasible solution that is likely close to optimal, but cannot guarantee that the true global optimum is found.

In the EU-S scenarios, the optimisation problem was solved by iteratively solving quadratic and linear programming problems. First, new feed rations for all animal species that exclude imported soybean feeds were found, using quadratic programming to minimise the difference between new feed rations and the feed rations in the baseline, while maintaining the supply of energy, protein and essential amino acids to animals. Constraints on the maximum inclusion of some feeds were also introduced (*e.g.* rapeseed meal for pigs and poultry). Then, based on the new feed rations, linear programming was used to find the optimal number of each animal species in each EU member state, in order to maximise the supply of human-edible protein in the form of animal-source foods based on the available feed resources in each scenario. Finally, total feed use in the solution was checked against the pool of available feeds. As the nutritional composition of different feeds makes them more or less suitable to replace soybean meal in rations, some feeds will limit animal-source food production (*i.e.* be fully utilised), while other feeds will be under-utilised. Weights were therefore applied to the quadratic programming goal function to aim for higher inclusion of feeds that were under-utilised and lower inclusion of feeds that were fully utilised. The procedure was then iterated until it converged to a final solution. See the methods section in **Paper IV** for a more detailed description of the optimisation model.

4.2.4 Land use calculations

For the FND scenarios (**Papers I** and **II**), land use for all crop production was calculated based on yield data from the respective national statistics agency. To account for the shift to organic agriculture, yields were factored with crop-specific values for the difference between conventional and organic yields taken from de Ponti *et al.* (2012), which on average gave a 20% yield reduction. The yield of ley in Finland, Norway and Sweden was multiplied by a factor of 1.7, based on data from Swedish field trials (Gunnarsson *et al.* 2014). This was to account for the fact that current ley management is often sub-optimal and that it is common practice to salvage some regrowth through grazing, which is not accounted for in the national crop statistics. For the results presented in Chapter 5 of this thesis, land use from imported products was calculated based on data in Moberg *et al.* (2020), which provides an update of the data used in **Papers I** and **II**.

For the EU-S scenarios (**Paper III**), cropland use was calculated for all crops produced with the primary purpose of feeding animals. The use of by-products such as rapeseed meal, cereal brans and low-grade crops therefore did not contribute to land use in the calculations, while products where the feed component is the primary product (*e.g.* soybean meal and vegetable oils other than soybean oil) bore the full land use from crop cultivation. Additional production of plant-source foods and vegetable oils introduced as a consequence of each scenario was also accounted for in the land use calculations, which thus followed a consequential modelling approach (Ekvall & Weidema 2004). Trade was accounted for in the baseline scenario by first estimating the volume of imports from outside the EU for each feed component. The remaining feed use in each EU member state was assumed to be produced domestically, as long as feed use did not exceed domestic production. When this was the case, feeds were assumed to be imported from other EU member states with excess production. In the scenarios, reduced feed use was assumed to first affect extra EU imports, then intra-EU imports and finally domestic production. After accounting for trade, arable land use was calculated based on country-specific yield data from Eurostat (European Commission 2022) for EU production and from FAOSTAT (FAO 2022) for production outside the EU.

4.2.5 Environmental impact assessments

In the FND scenarios, environmental impacts were assessed by tracking emissions of carbon dioxide, nitrous oxide, methane, ammonia, sulphur dioxide and nitrogen oxides to the air, as well as nitrogen and phosphorus leaching losses to water bodies. Emissions were calculated mainly using IPCC (2006) guidelines, but also based on other sources (see **Papers I** and **II** and Karlsson *et al.* (2017) for further details). The system boundary was drawn at farm gate for all Nordic production and at the shoreline for fisheries. Climate impact was calculated as global warming potential over 100 years (GWP_{100}) according to the 5th IPCC assessment report (IPCC 2013).

For the results presented in Chapter 5 of this thesis, the literature values used to estimate impacts from food imports (*i.e.* coffee, tea, cocoa, nuts, banana and citrus fruit) were updated compared with results presented in **Papers I** and **II**, based on new data in Moberg *et al.* (2020). These data refer to impacts from cradle to Swedish retail gate, but were assumed to be representative also for the other Nordic countries.

Apart from flows to the environment, nitrogen and phosphorus flows within the system were also quantified for the two scenarios. To balance the system, any soil deficits in nitrogen and phosphorus were assumed to be covered by additional nitrogen and phosphorus from an 'unknown external source', which were also accounted for as nitrogen additions to soils in estimating nitrous oxide emissions. For the results presented in Chapter 5 of this thesis, GHG emissions associated with production of these additional inputs were also added to the climate impact of diets, assuming production of conventional nitrogen and phosphorus fertiliser, with 5.4 kg CO_2e per kg nitrogen (Symeonidis 2021b) and 6.2 kg CO_2e per kg phosphorus (Symeonidis 2021a) according to the ecoinvent database.

In the EU-S scenarios, product- and country-specific literature factors for land use change-related carbon dioxide emissions (Henders *et al.* 2015) and biodiversity impacts (Chaudhary & Kastner 2016) were used to estimate impacts from net changes in global demand for soybean and palm oil.

4.3 Non-provisioning ecosystem services indicator suite

In **Paper IV**, a suite of indicators for non-provisioning ecosystem services was developed and calculated for a large subset of Swedish farms (44 468 farms with a total agricultural area of 2.5 Mha, covering 81% of Swedish agricultural land). The indicators were based on previous studies assessing trade-offs and synergies between multiple ecosystem services from a landscape perspective (*e.g.* Raudsepp-Hearne *et al.* 2010; Turner *et al.* 2014; Andersson *et al.* 2015; Queiroz *et al.* 2015). The indicator suite included nine indicators, which were calculated over a study area for each farm defined by drawing a 50-m buffer around each farm's agricultural land.

To avoid biased interpretation of results from including strongly correlated indicators, two indicators were dropped from the analysis. The remaining seven indicators included in all analyses were:

Landscape variation (LanVar), calculated as the length of borders between different land cover patches divided by the total study area. This indicator relates to ecosystem services such as habitat creation, pollination and pest control (Rundlöf *et al.* 2008; Chaplin-Kramer *et al.* 2011; Persson *et al.* 2015).

Semi-natural grasslands (Gra), calculated as the area of semi-natural grasslands divided by the total agricultural area. Grasslands also present in the Swedish meadow and pasture inventory were weighted with a factor of 2, as grasslands present there generally hold higher biological and cultural values. Semi-natural grasslands promote a number of ecosystem services, including climate regulation, water supply, erosion control, providing habitats for pollinators and natural enemies, as well as cultural services in terms of recreation and cultural heritage (see Bengtsson *et al.* (2019) for a review).

Small-scale habitats (SSHab), calculated as the number of 'holes' found in cropland polygons (often consisting of field islets, trees, clearance cairns *etc.*) divided by the total cropland area. More small-scale habitats can provide habitats and dispersal corridors for beneficial insects (Thomas *et al.* 1991; Arlt *et al.* 2019).

Crop Sequence (CrpSeq), calculated by applying a crop sequence indicator developed by Leteinturier *et al.* (2006), which accounts for the beneficial or detrimental effects of different combinations of preceding and subsequent crops, to crop sequences from 2013 to 2019. This indicator relates to ecosystem services such as soil fertility building (Albizua *et al.* 2015; Tiemann *et al.* 2015), disease, pest and weed suppression (Ball *et al.* 2005; Rusch *et al.* 2013) and nitrogen fixation (Nevens & Reheul 2002).

Accessibility (Acc), calculated as a combination of farm study area within 100 m from roads and the population density within a 10-km buffer around each farm's study area. This indicator aims to capture ecosystem services related to recreation and tourism where accessibility is an important prerequisite.

Visitors (Visit), calculated as a combination of unique users reporting species to the species database *Artportalen* and uploading photos to *Flickr* within each farm's study area divided by the total study area. The number of visitors were assumed to correspond to ecosystem services related to nature recreation.

Nature conservation and recreation areas (NatRes), calculated as the total area within a farm's study area designated for different nature conservation and recreation purposes (*e.g*. nature reserves, Natura-2000 areas) divided by the total study area. This indicator relates to ecosystem services such as habitat creation and maintenance, as well as recreation and tourism.

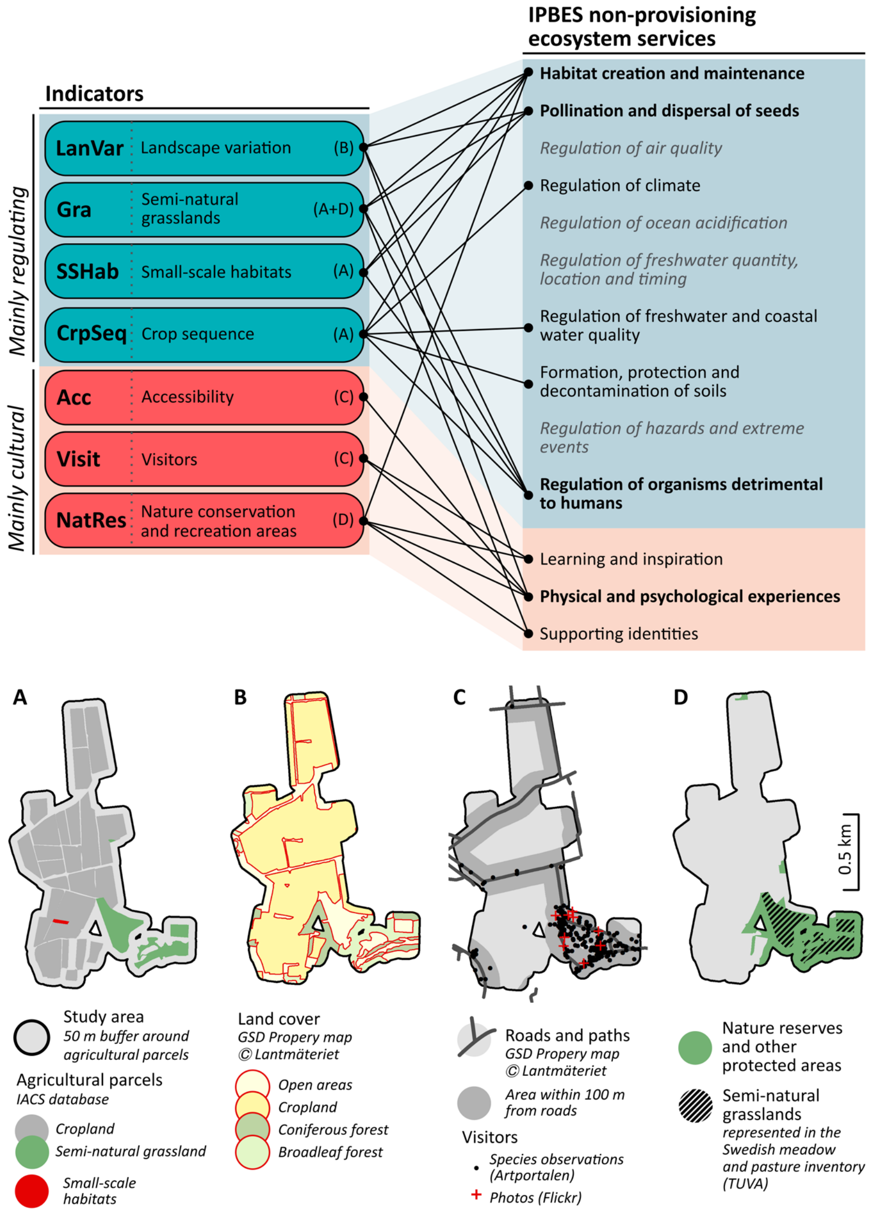

Figure 6. Upper panel: The seven indicators and assumed correspondence to non-provisioning ecosystem services. Lines indicate that a higher value on the indicator is assumed to correspond to increased supply of the connected ecosystem service. Lower panel: Maps of a selected farm study area illustrating the different datasets used in calculating the different indicators. For each indicator (upper panel), the letters in brackets (A-D) indicates the datasets (map(s) in lower panel) used in its calculation.

A number of datasets were used in calculating the different indicators, including the Swedish farm register (Swedish Board of Agriculture 2018) and the Integrated Administration and Control System (IACS) database, which include georeferenced data on all agricultural parcels for which farmers have applied for agricultural support, and *e.g.* land cover maps. **Figure 6** provides an illustration of the seven indicators and the ecosystem services to which they were assumed to correspond, and the datasets used in calculations. For a more detailed description of the indicators and their links to different ecosystem services, see **Paper IV** including its Supplementary Material (SM).

All farms were grouped into types based on the number of standardised working hours spent on different farm activities (*e.g.* dairy cows, wheat production *etc.*) according to the Swedish farm typology (Swedish Board of Agriculture 2002). Farms were classified as belonging to a specific type if more than two-thirds of working hours were spent on that activity. Five main farm types were used in analyses: Crops, ruminants, monogastrics, mixed (where crops, ruminants or monogastrics do not contribute more than two-thirds of working hours) and small-scale farms (farms with less than 400 standardised working hours). For the results presented in Chapter 5 of this thesis, the type 'horses' was also introduced, defined as all farms where horses contributed more than three-quarters of total livestock units and ley was grown on more than three-quarters of arable land. This resulted in 34%, 13%, 3.5%, 0.6% and 0.5% of small-scale, crop, mixed, monogastric and ruminant farms, respectively, being redefined as horse farms.

Prior to analysis, indicator values were scaled and normalised so that a value of zero represented the mean indicator value for all farms and a value of plus/minus one was one standard deviation above/below the mean.

To avoid confounding effects of different farm types being concentrated in certain regions where *e.g.* natural preconditions lead to lower or higher scores on the indicators, differences between farm types were analysed by first calculating the difference (D) in indicator value (I) from the area-weighted mean indicator value of surrounding farms specialised in crop production according to:

$$D_a = I_a - \frac{\sum I_k \cdot A_k}{\sum A_k} \qquad (1)$$

where a is the farm under study, A is total farm area, and k is all farms within a 20-km radius of farm a.

After calculating D for all farms, Welch's unequal variances t-tests were used to test for statistical significance (α=0.01) of observed differences in mean D for the different farm types compared with crop production farms. Effect size was estimated using Cohen's d, with a variance term matching that in Welch's t-test (Aoki 2020). Effect size was categorised as: large ($|d|>0.8$), moderate ($|d|>0.5$), small ($|d|>0.2$) or otherwise negligible (Cohen 1977).

For landscape variation (LanVar), a generalised additive model (GAM) including farm size, livestock density[2] of cattle, sheep, horses and monogastric animals and geographical location as explanatory variables was also used to describe differences in indicator values (**Paper IV**).

[2]Livestock units per hectare total agricultural land.

5. Results and discussion

5.1 Livestock as resource users – *The FND and EU-S scenarios*

Results from the FND scenarios (**Papers I** and **II**) showed that complete diets could be provided for 31 and 37 million people in the SY and EY scenario, respectively, which is 9–30% more than the projected Nordic population in 2030 (United Nations 2017). This shows that reduced food-feed competition can allow for less intensive agricultural practices such as organic farming and taking agricultural land out of production for nature conservation, while still providing a large food output, as also demonstrated by Muller *et al.* (2017). However, there were large variations between the Nordic countries. While Danish agriculture could support more than twice Denmark's population in 2030, Norway could only support up to half its projected population. This mirrors the current state of food self-sufficiency among the Nordic countries (Pradhan *et al.* 2014; Beltran-Peña *et al.* 2020) and shows the importance of food trade for the food security of some populations.

The EU-S scenarios (**Paper III**) showed that ceased soybean feed imports, while avoiding increased EU cropland use for feed production, could reduce non-EU cropland demand by 11–14 Mha (for reference this approximately equates to the entire cropland area of Germany or Spain) and total supply of edible protein and fat from EU livestock production by 18–25%. This reduction was compensated for in the scenarios by an increased supply of plant-source foods. In the different scenarios, 0–8.9 Mt of soybean imports (equivalent to 0–22% of current imports used for feed) were needed to compensate for reduced supply of edible protein from animal-source foods. No soybean imports were needed in the FOOD scenario where additional food legumes were grown in the EU. In addition, demand for palm oil changed by -0.3 to +7.5 Mt to compensate for reduced supply of animal-source fat and soybean oil (an effect of reduced soybean meal use). The negative demand for palm oil production was observed in the OIL scenario where increased EU rapeseed oil production exceeded reduced animal source fat and soybean oil supply.

In the remainder of this section, results from analyses of the FND and EU-S scenarios are presented and discussed in terms of livestock production (section 5.1.1), land use (section 5.1.2), diets and nutrition (section 5.1.3) and environmental impacts (section 5.1.4).

5.1.1 Livestock production

In both the FND and EU-S scenarios, ruminant animals were favoured over monogastric animals when optimising for food output (**Figure 7**), which is in line with other studies of livestock limited to leftovers (van Hal *et al.* 2019; van Selm *et al.* 2022) or transitions towards agroecological/organic farming (Poux & Aubert 2018; Barbieri *et al.* 2021).

In the FND sufficiency (SY) scenario, ruminants were limited to the minimum number required to graze all semi-natural grasslands currently available, resulting in a 74% and 72% reduction in the number of cattle and sheep, respectively, in the Nordic countries. In the efficiency (EY) scenario, the number of ruminants was allowed to increase to make use of all ley included in the organic crop rotations, which led to cattle numbers equivalent to 85% of the current Nordic herd and a 30% increase in the number of sheep. The number of pigs slaughtered was reduced by 96–99% in the FND scenarios, and the number of laying hens by 72% in SY and 15% in EY. van Hal *et al.* (2019) found a similar favouring of ruminants in their optimisation model, but relatively more pigs and fewer poultry compared with the FND-EY scenario. This can be explained by food waste being considered a feed source that was mainly fed to pigs in their scenarios, while poultry numbers were limited by the quality of available leftovers. The higher inclusion of poultry in scenario EY compared with SY was explained by an overly high protein-to-energy ratio in available by-products, which was compensated for by inclusion of cereal grains grown on leftover arable land in the EY scenario. The observed reduction in aquaculture production (62–63%) in the FND scenarios was mainly due to the current large-scale salmon farming in

Norway, producing 1.3 Mt live weight annually and heavily relying on forage fish and soybean feeds (Pelletier *et al.* 2009; Cashion *et al.* 2016), which were not allowed in the scenarios. In the other Nordic countries, where aquaculture is currently a small sector, aquaculture increased six to 14-fold in the scenarios.

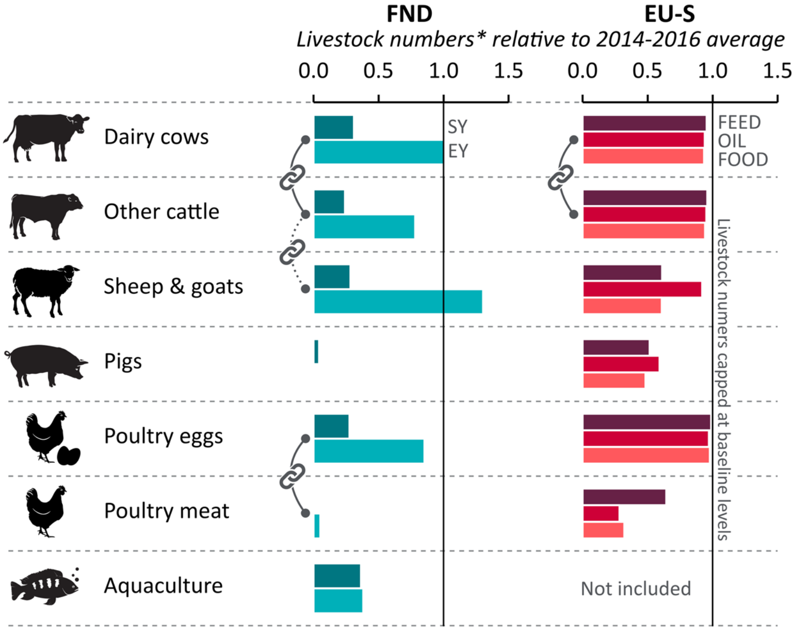

Figure 7. Number of animals in the FND and EU-S scenarios relative to the Nordic/European Union average for 2014-2016 according to FAOSTAT (FAO 2022). The lines with link symbols indicate that these animal categories were linked in the models and could not vary independently. *Comparisons are made based on numbers slaughtered for pigs and poultry meat, live weight production for aquaculture and number of head for the other livestock categories.

In the EU-S scenarios, cattle and laying hens were favoured in the optimisation model and their numbers remained relatively unchanged in the scenarios. The number of sheep and goats decreased by 39% in the FEED and FOOD scenarios, due to a strong reduction in Northern European countries where sheep and goats are not used in milk production, which results in a low yield of human-edible protein per kg feed in these systems. The number of pigs and poultry slaughtered was reduced by 41–52% and 36–72%, respectively, in the scenarios.

In all EU-S scenarios, the number of each livestock species in each country was capped at baseline levels in order to ensure scenarios where livestock production is not concentrated to a limited number of countries and livestock species. Sensitivity analysis showed that lifting this cap for the FEED scenario led to a more than four-fold increase in egg production compared with the baseline and more poultry meat compared with the original FEED scenario, at the expense of mainly pig meat production (**Paper III, SM**). Constraints placed on the maximum allowable inclusion of rapeseed meal in the diets of poultry were found to limit their inclusion in the scenarios. Sensitivity analysis on the OIL scenario showed that lifting this constraint led to a three-fold increase in poultry meat compared with the original OIL scenario, at the expense of pig meat (**Paper III, SM**).

The reason that ruminants were favoured in the optimisation models is their ability to make use of grass and other roughages. In the FND scenarios, biomass from land use leftovers and leys accounted for 69% (SY) and 77% (EY) of feed dry matter, while in the EU-S scenarios roughages accounted for 62–64%. For reference, roughages accounted for 60% in the EU baseline. For ruminants to utilise these feed resources fully, some additional feeds were also needed to meet animal feed requirements, which made it favourable to allocate some of the higher quality feeds in the form of by-products and grains to ruminants. In the FND-SY scenario, 18% of by-products were allocated to ruminant animals, which increased to 47% in the EY scenario as an effect of the larger ruminant herd needed to use all cropping system leftovers. This led to lower availability of by-products for pigs, poultry and aquaculture in this scenario compared with SY. The feed grains introduced on leftover arable land in the EY scenario were primarily used by poultry (51%), with the remainder split between use for ruminants and aquaculture. In the EU-S scenarios, the share of by-products used by ruminants increased from 43% in the baseline to 51–56% in the different scenarios, and the share of grains used by ruminants increased from 19% to 40–46%. In should however be noted that the scenarios resulted in a reduced use of feed grains in total.

In the EU-S scenarios, animal productivity and thus feed requirements were assumed to be unchanged compared with the baseline, while in the FND scenarios productivity levels were set *a priori* to reflect organic practices and durable lower-yielding breeds. If the models had been more flexible and allowed for optimisation of animal productivity and thereby feed requirements, it is likely that less productive, grass-based ruminant systems allowing for higher use of non-roughage feed resources by monogastrics would have enabled more efficient utilisation of available resources. This has previously been observed in a study by van Hal *et al.* (2019), where optimal use of leftovers favoured low-yielding dairy production systems.

Apart from the reduced inclusion of soybean meal, animal feed rations in the EU-S scenarios changed towards higher inclusion of pulses and protein-rich by-products and lower inclusion of cereals in the diets of monogastric animals, while ruminant feed rations changed to include more cereals and protein-rich by-products and less maize silage compared with the baseline (**Paper III, SM**). These results show that reduced use of soybean meal in ruminant diets reduced the potential to incorporate low-protein maize silage in rations. Thus, the current trend towards more maize silage-based rations (Reheul *et al.* 2010) may exacerbate dependency on soybean meal and other protein-rich concentrates. Instead, incorporating more grass-legume based silages in rations could increase on-farm protein production (Lüscher *et al.* 2014) and reduce the need for other sources of feed protein.

5.1.2 Land use

Both FND scenarios resulted in a shift in cropland use from a dominance of leys and cereals to a more diversified use, including larger areas of oil crops, pulses, roots and vegetables, and permanent crops (*i.e.* fruit trees) (**Figure 8**). The area of oil crops increased from 4% to 13% of arable land and the area of pulses increased from 1.0% to 4.3% and 3.5% of arable land in SY and EY, respectively. Although the area of pulses in the scenarios still made up a small fraction of cropland, agronomic challenges with growing these crops in the Nordic climate may pose challenges (Röös *et al.* 2018a). However, a previous assessment of the potential for pea and broad bean cultivation in Sweden found that increased cultivation of up to 150 000 ha is feasible (Gustafsson *et al.* 2013), which is comparable to the area of pulses in Sweden in the FND scenarios (116 000-149 000 ha). The increased rapeseed oil production would likely also be highly challenging, considering that rapeseed would need to be cultivated on average once every seventh years on all arable land where climate conditions allow. The area under permanent crops increased from the current 0.04 Mha up to 0.7 Mha in EY. This dramatic increase was explained by the healthy baseline diet containing around twice as much fruit as the current Nordic diet, which was covered by increased Nordic production, and by all fruit juice in the diet being produced from Nordic fruit. Fruit imports in the scenarios were only assumed to cover current consumption levels of banana and citrus fruit, while the remaining fruit in the diet was produced within the Nordic region.

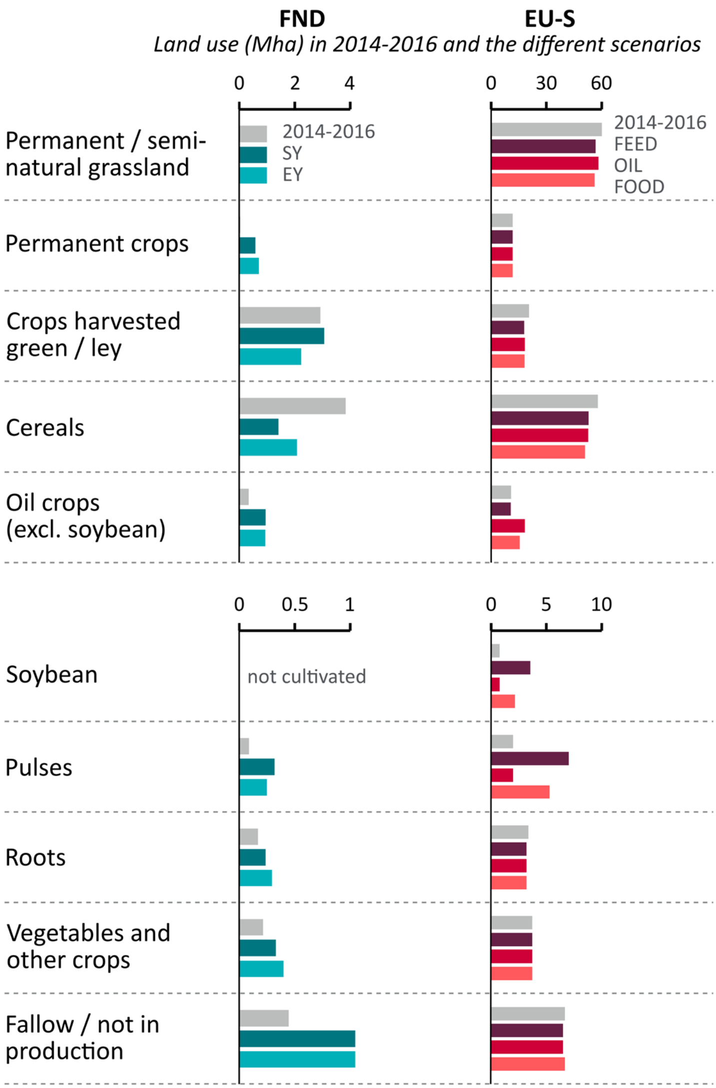

Figure 8. Land use in the FND and EU-S scenarios compared with current (2014-2016) Nordic/European Union land use according to Eurostat (European Commission 2022) except for semi-natural grasslands in the Nordic countries, where areas are based on data collected by the stakeholders in the FND project.

In the EU-S scenarios, cropland demand outside the EU was reduced by 11–14 Mha as a net effect of reduced demand for feed imports (mainly soybean) and increased demand for plant-source protein and fat. Total cropland use within the EU was held constant across scenarios, but differed in terms of crops grown. In the FEED scenario, cultivation of pulses (including soybean) increased from 3% to 10% of EU cropland, while in the OIL scenario cultivation of oil crops increased from 10% to 17% of EU cropland. In the FOOD scenario, pulses (including soybean) and oil crops increased to 7% and 15% of EU cropland, respectively. In the OIL scenario oilseeds would be grown on average once every sixth year on all arable land in the EU, which is close to or beyond what can be considered agronomically feasible.

In the FND scenarios, constraints on the maximum inclusion of rapeseed in crop rotations (on average no more than once every seven years) were found to limit production. To keep rapeseed cultivation within the set constraints, additional ley (SY scenario) or ley, cereals and pulses (EY scenario) were introduced to the crop rotations. As diets were high in carbohydrates and on the lower limit for recommended fat intake (**Figure 9**), these crops could not be used directly for human consumption without resulting in imbalanced diets. Thus, crops introduced to limit rapeseed cultivation frequency could be considered as cropping system leftovers under the constraint that the Nordic land base should produce complete diets. In the EY scenario these were used for animal feeding, which allowed a larger population to be provided with a balanced diet. This result shows the importance of accounting for both production- and consumption-side limitations in food systems, to assess which resources become 'leftover' from direct food production and where livestock production may allow for valorisation of these resources. It also shows the importance of accounting for fat in scenarios of reduced animal-source food consumption, where the focal point is often on protein (Bajželj *et al.* 2021). The importance of fat was also noted in the EU-S scenarios, where 62–81% of land needed to compensate for reduced animal-source food consumption and soybean oil production could be attributed to fat[3]. This is especially important considering that global production and consumption of fat need to increase to meet recommended levels of consumption, and that food uses of fat are under increased competition from the energy system (Bajželj *et al.* 2021).

[3]Land use was allocated to fat for each product (soybeans, broad beans, field peas, rapeseed oil, palm oil) based on relative mass of protein and fat: Land use (fat) = Land use × (Weight (fat) /Weight (fat + protein)).

Currently, 26-48% of global vegetable oil production (depending on data source) is destined for non-food uses (Bajželj *et al.* 2021), competition that will likely increase in the future especially if phase-out of fossil fuels relies on fat-based bioenergy. Similarly, Troya *et al.* (2021) estimated that supply of saturated (animal-like) fats of plant origin is a bottleneck for meeting future demand for plant-based meat.

5.1.3 Diets and nutrition

In the FND scenarios, animal-source food contributed 14 g (SY) to 29 g (EY) protein per capita and day in the diets. This is around a quarter to half of the 56 g cap^{-1} day^{-1} in the current Nordic diet[4], and in line with previous livestock on leftovers scenarios showing contributions of 9–23 g cap^{-1} day^{-1} from animal-source food (Van Zanten *et al.* 2018). The EY scenario was above the range of previous estimates, likely as a net effect of the organic cropping systems generating considerable cropping system leftovers in the form of ley biomass and because assumptions regarding what comprises land use leftovers were stricter than in other studies. Later livestock on leftovers studies by van Hal *et al.* (2019) and van Selm *et al.* (2022), reported 31 and 40 g protein cap^{-1} day^{-1} from animal-source food, respectively. These studies included retail and household food waste as a feed source for pigs and poultry, which was not included in the FND scenarios and is currently not allowed under EU legislation.

In the EU-S scenarios, terrestrial animal-source protein supply (before post-farm losses) was reduced from 64 g cap^{-1} day^{-1} in the baseline to 49–53 g cap^{-1} day^{-1} in the scenarios, a 17–24% reduction.

Looking at specific animal-source foods (**Table 3**), it was found that meat consumption was substantially reduced in both FND scenarios to 80–150 g per week, equivalent to around one weekly serving of meat, compared with around seven servings in current diets. Meat from ruminants was relatively less affected, with more than half of current ruminant meat consumption remaining in the EY scenario. Milk consumption was reduced by 63% in the SY scenario, while milk consumption was on the same level as in current Nordic diets in the EY scenario. Fish produced from aquaculture in the Nordic region and a 'fair share' of wild-caught fish resulted in 130–140 g of

[4]Based on national dietary surveys for total protein intake and assuming that 64% of this is from animal-source food based on FAOSTAT data (FAO 2022).

fish per week in the FND scenarios, which is around half of current fish consumption. Egg consumption was around half of current consumption in the SY scenario, while the inclusion of some cereal grains for poultry feed in the EY scenario allowed consumption of eggs in line with current diets.

In the EU-S scenarios, the supply of milk and meat from ruminant animals was relatively unchanged (up to 10% reduction in ruminant meat), as was the supply of eggs. For pig and poultry meat, substantial reductions of 34–71% were observed across the different scenarios, with a stronger reduction in poultry meat in all scenarios except FEED due to limits on the maximum inclusion of rapeseed meal in poultry diets.

Table 3. *Changes in per-capita consumption/production of different animal-source foods in the FND and EU-S scenarios. The shaded numbers indicate percentage change in consumption/production in the scenarios compared with current consumption/baseline*

	Meat (g week^{-1}, without bones)			Eggs	Milk[1]	Fish
	Ruminant	Pig	Poultry	(g week^{-1})	(L week^{-1})	(g week^{-1})
FND scenarios						
Values refer to raw weight quantities consumed after accounting for all losses						
Cur. Cons.[2] (~2010)	240	350	180	140	2.0	290
SY	47 *-80%*	28 *-92%*	4.2 *-98%*	55 *-60%*	0.8 *-63%*	140 *-52%*
EY	130 *-44%*	4.8 *-99%*	11 *-94%*	140 *+4%*	2.0 *-1%*	130 *-55%*
EU-S scenarios						
Values refer to EU production divided by EU population						
Baseline (2014-2016)	220	520	410	270	7.2	
FEED	210 *-8%*	270 *-49%*	270 *-34%*	270 *-1%*	6.9 *-4%*	
OIL	210 *-6%*	310 *-41%*	120 *-71%*	260 *-2%*	6.9 *-5%*	
FOOD	200 *-10%*	250 *-51%*	130 *-68%*	260 *-2%*	6.8 *-5%*	

[1]For the FND scenarios, values refer to milk consumed as such (*i.e.* excluding other dairy products), while for the EU-S scenarios values refer to raw milk production
[2]Current consumption based on national dietary surveys conducted around 2010 to 2012.

Macronutrient supply

In the FND scenarios, the contribution of protein and fat to dietary energy intake met Nordic nutrition recommendations of at least 10% and 25%, respectively (Nordic Council of Ministers 2014), but were at the lower end of the permitted range, while the contribution of carbohydrates slightly exceeded the upper limit of 60% of energy intake (**Figure 9**). In the EU-S scenarios, supply of protein and fat was unchanged, as the scenarios were designed to maintain these at baseline levels.

Micronutrient supply

Regarding micronutrients, intake of calcium, iron, vitamins A, B_{12}, D and riboflavin was found to be low in one or both of the FND scenarios. Supply of vitamins A and B_{12} was also reduced in the EU-S scenarios compared with the baseline (**Figure 9**).

Calcium intake was below recommendations in the FND-SY scenario, but the higher inclusion of milk in the FND-EY scenario increased calcium intake to a level meeting recommendations. In the EU-S scenarios, calcium supply was relatively unchanged due to the small changes in raw milk production.

Iron intake increased marginally in both FND scenarios compared to current intake, but was still lower than recommendations in the EY scenario. In the EU-S scenarios, iron supply increased significantly due to increased supply of soybean for direct human consumption. However, it should be noted that haem iron, found only in meat, has higher bioavailability than the non-haem iron found in other plant and animal sources (Heath & Fairweather-Tait 2002). Nevertheless, after accounting for this difference in bioavailability, and assuming a lower iron content in soybeans, the scenarios still resulted in an increased iron supply compared with the baseline (**Paper III, SM**). Studies on the relationship between iron status and meat intake have shown variable results, but generally indicate that lower meat intake is associated with lower iron stores in the human body (Jackson *et al.* 2016; Haider *et al.* 2018). The results obtained in this thesis indicate that reduced animal-source food consumption in line with the FND and EU-S scenarios would not negatively affect iron status if appropriately replaced with iron-rich plant sources such as pulses.

Zinc intake met recommendations in both FND scenarios and was relatively unchanged in the EU-S scenarios. European countries also currently meet recommendations for zinc (Rippin *et al.* 2017).

Vitamin A intake was found to be below recommendations in both FND scenarios and decreased slightly in the EU-S scenarios. Vitamin A is one of few micronutrients for which livestock production is a net source (**Table 1**). European countries generally meet recommendations for vitamin A intake (Efsa Panel on Dietetic Products & Allergies 2015) and the slight reductions in supply observed in the EU-S scenarios are likely not problematic for vitamin A intake. For the FND scenarios, increased inclusion of *e.g.* carrots or other vegetables rich in carotene in the diets is an option, but considering the large shortfall relative to recommendations, this may not be sufficient.

Vitamin B_{12} is exclusively found in animal-source foods and intake was thus reduced in both FND scenarios compared with current intake, and supply decreased in the EU-S scenarios compared with the baseline. In FND-SY, intake was below recommendations, while in FND-EY intake met recommendations. In Europe, most countries comfortably meet B_{12} recommendations (Rippin *et al.* 2017) and reduced animal-source food supply in line with the EU-S scenarios is likely not problematic for adequate vitamin B_{12} intake.

Vitamin D intake was below recommendations in both current Nordic diets and the FND scenarios. Adequate dietary intake of vitamin D is highly challenging unless large quantities of fatty fish are consumed, especially considering recommendations to limit UVB light exposure (which is an important source of the vitamin). Food fortification and dietary supplements have been proposed as the most feasible strategies to achieve adequacy (Calvo *et al.* 2005), which would also apply to the FND scenario diets.

Riboflavin intake was found to be low in the FND-SY scenario, but met recommendations in the EY scenario due to increased intake of dairy and other animal-source foods. Riboflavin supply increased in all EU-S scenarios, mainly due to maintained milk supply and increased supply of soybean. Soybean has a relatively high riboflavin content according to the USDA FoodData Central, which was used for nutrition calculations.

Folate intake is currently below recommendations in the Nordic countries, as in most European countries (Rippin *et al.* 2017). In both FND scenarios, folate intake met recommendations due to increased consumption of pulses, vegetables and fruit compared with current diets.

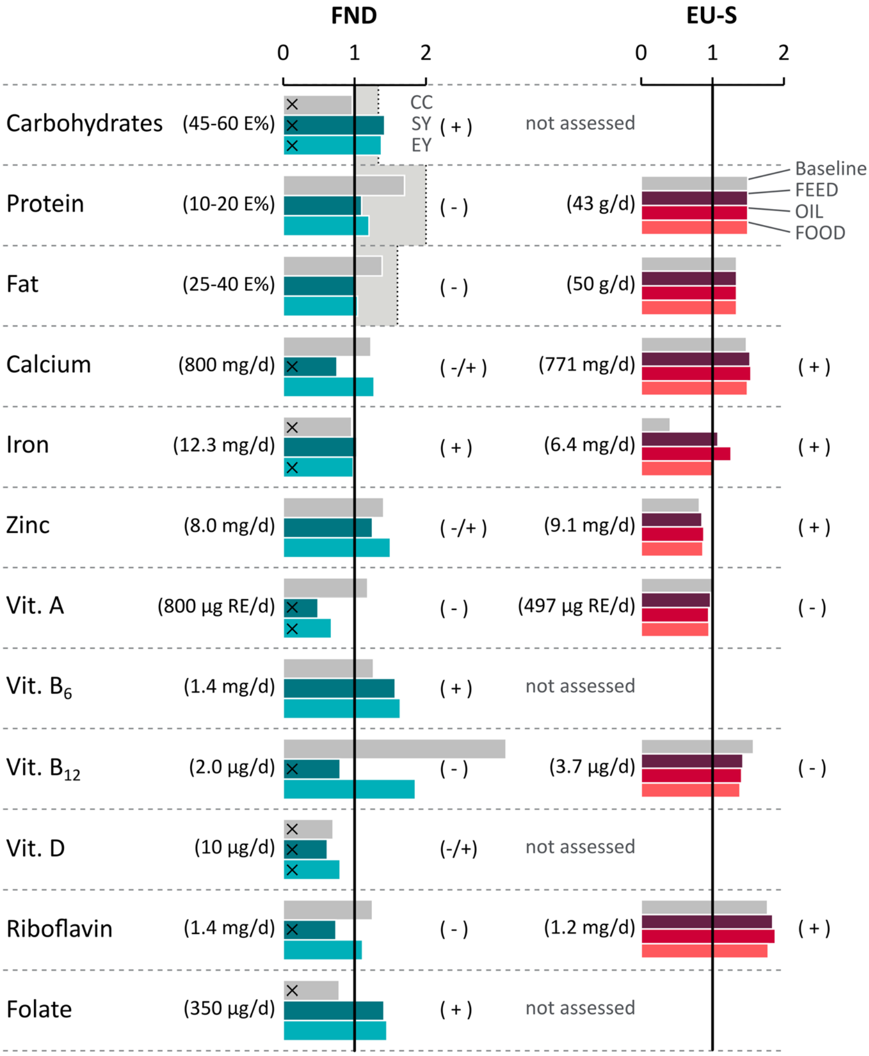

Figure 9. Macro- and micronutrient supply in the FND and EU-S scenarios. For the FND scenarios, nutrients in the diets after accounting for all losses are expressed in relation to Nordic Nutrition Recommendations (Nordic Council of Ministers 2014) shown in brackets. The values for the current consumption (CC) are also shown. For the EU-S scenarios, nutrients present in the edible parts of animal-source foods and plant-source protein and fat replacements *before* accounting for post-farm losses are expressed in relation to EU dietary reference values (European Food Safety Authority 2017) for the EU population's weighted average requirements shown in brackets (for vitamin B_{12}, adequate intake values are used). A plus or minus sign indicates whether the scenarios increased (+) or decreased (-) the supply of that nutrient relative to the current situation.

5.1.4 Environmental impacts

Comparison of results from the FND scenarios to the food system planetary boundaries for climate, nitrogen, phosphorus and cropland use proposed by Willett *et al.* (2019) showed that the scenarios transgressed the per-capita boundaries for nitrogen, phosphorus and cropland use (**Figure 10**). The global boundaries were downscaled to per-capita by dividing the absolute values by the projected global population in 2030, in line with Moberg *et al.* (2020). All EU-S scenarios considerably reduced cropland demand in deforestation-prone regions, but shifted demand from South America (soybean) to Southeast Asia (palm oil) in two out of three scenarios.

Nitrogen and phosphorus flows in the FND scenarios

The boundary for nitrogen refers to 'new' reactive nitrogen added to soils, which in the scenarios comprised the sum of biological fixation in the Nordic countries, nitrogen fertiliser inputs in production of imported foods and nitrogen from an 'unknown source' needed to balance Nordic soil inputs against outputs and losses. Similarly, for phosphorus the total addition of new phosphorus comprised fertiliser use for imported foods plus the additional phosphorus needed to balance Nordic soils. Increased recirculation of nutrients from society could potentially contribute towards remaining within the planetary boundaries by reducing the need for these 'unknown sources' of nitrogen and phosphorus. In the scenarios, nutrients present in food waste, manure and biogas digestate were already assumed to be used on croplands, while nutrients in foods consumed were not. Practically all nutrients consumed through the diet end up in urine and faeces (Jönsson *et al.* 2004) and could be recovered at household level or treatment plant level and recirculated back to arable soils through a number of recovery pathways (Harder *et al.* 2019). Full recovery is likely not technically or practically feasible, but Simha (2021) found that use of urine-diverting toilets and subsequent urine drying could recover up to 86% of nitrogen and 67% of phosphorus in human excreta in a dry fraction (assuming that 88% of excreted nitrogen and 67% of phosphorous is found in the urine; Jönsson *et al.* 2004). Recovering the faeces too could theoretically increase this potential even further, especially for phosphorus. As an indication of the potentially recyclable nutrients in human excreta, the arrows in **Figure 10** show the contribution to meeting the planetary boundaries if half of nutrients consumed in the diet were to be recycled. Overall, **Figure 10** shows that, even under optimistic assumptions on nutrient circularity, suggested planetary boundaries are still transgressed and both nitrogen and phosphorus deficits persist in the all-organic scenarios. It should be acknowledged, however, that imported foods were assumed to be produced under conventional farming, which made a considerable contribution to phosphorus use in particular. If imported foods were also produced in systems that are more circular, these impacts would be lower.

These results show that adequate nitrogen and phosphorus supply is challenging under scenarios of a complete transition to organic farming. Similarly, Barbieri *et al.* (2021) concluded that nitrogen supply is a limiting factor for large-scale conversion to organic agriculture while feeding a growing human population. In addition, assessments of nutrient exchanges between conventional and organic farms in France have shown that organic farms rely on conventional farms for 23% and 73% of their nitrogen and phosphorus supply, respectively (Nowak *et al.* 2013). This further shows the challenge of adequate nutrient supply in organic farming systems. Closing the remaining nitrogen gap in the FND scenarios could potentially be achieved through increased ley cultivation, but that would reduce total food output from the scenarios. Alternatively, increased nitrogen fixation could be achieved by incorporating leguminous cover crops into the cropping systems, which could simultaneously reduce leaching losses (Tribouillois *et al.* 2016), or by using renewable synthetic nitrogen fertiliser, although the latter option is not currently allowed in regulations for organic farming (Röös *et al.* 2018b). For phosphorus, deficits could be alleviated by recirculating phosphorus from agricultural runoff or from the sea (Spångberg *et al.* 2013; Roy 2017) or by using mined rock phosphate, which is an authorised fertiliser under EU organic regulations. Recirculation from sectors outside the food system could also be an option. For example, the volume of ash produced yearly in Swedish power generation and industry is estimated to contain 7,500 metric tonnes of phosphorus (Linderholm & Mattsson 2013), which equates to around three-quarters of the phosphorus deficit in the Swedish FND scenarios.

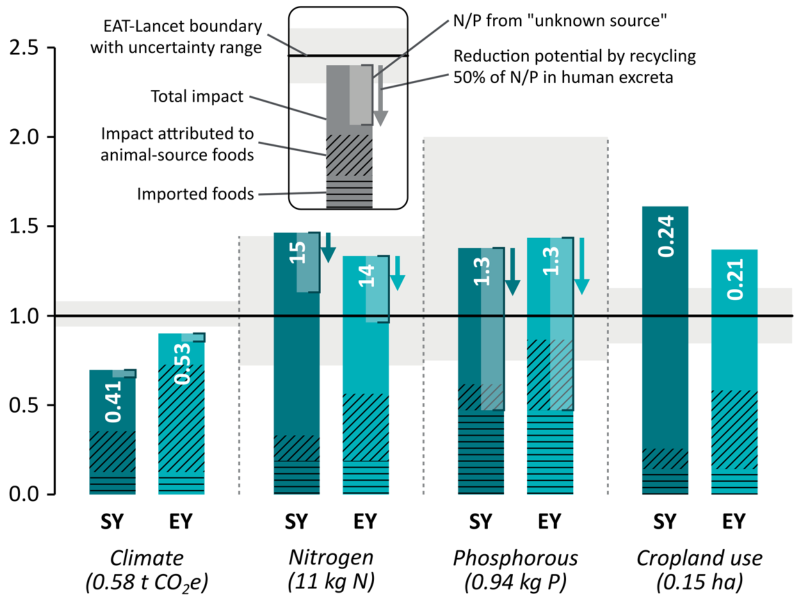

Figure 10. The FND scenarios compared with per capita EAT-Lancet boundaries for climate (*i.e.* GHG emissions), application of 'new' nitrogen (N) and phosphorus (P) and cropland use. Per capita boundaries (shown in brackets) were calculated by dividing the global boundaries from Willett *et al.* (2019) by the estimated global population in 2030, in line with Moberg *et al.* (2020). Compared with results presented in Papers I and II, two changes have been made: i) factors to calculate impacts from imported food have been updated based on data in Moberg *et al.* (2020) and ii) GHG emissions associated with production of additional nitrogen and phosphorus needed from 'unknown sources' have been added based on figures for conventional mineral fertiliser production.

Trade-off between cropland use and climate impacts in the FND scenarios

Cropland use per diet was lower in the EY scenario than in the SY scenario (**Figure 10**), due to more efficient utilisation of leftovers in the former, but transgressed the planetary boundary in both scenarios. The increased ruminant herd needed for efficient utilisation of leftovers resulted in larger GHG emissions in the EY compared with the SY scenario. There is thus a trade-off between using livestock to minimise cropland use and mitigating climate change. The climate impacts of the FND scenarios were estimated at 0.41 (SY) and 0.53 (EY) tCO_2e per diet and year, which are comparable to values found in another study on livestock on leftovers for the case of Europe (0.35–0.48 tCO_2e cap^{-1} $year^{-1}$; van Selm *et al.*, 2022). Both FND scenarios were within the suggested planetary boundary for climate change (**Figure 10**), which suggests that a livestock herd in line with a livestock on leftovers approach might strike a good balance between mitigating climate change and limiting cropland use and maintaining biodiverse semi-natural grasslands. It should be noted, however, that GHG emissions were only calculated up to farm gate, and thus excluded emissions occurring later in the food system. Considering that the suggested boundary for climate impact is defined as only including methane and nitrous oxide emissions (the boundary for net carbon dioxide emissions is zero), meeting this boundary would require a fossil-free energy system and thus potentially small emissions post-farm gate, depending on how the energy system develops. The current average Swedish diet is estimated to emit 2.0 tCO_2e (~1.7 tCO_2e up until farm gate[5]) and use 0.30 ha cropland per year (Moberg *et al.* 2021). Although methodological differences make direct comparisons difficult, it is likely that the FND scenarios would reduce GHG emissions substantially and use less cropland than current diets, despite the transition to lower-yielding organic farming with large areas of cropland devoted to ley cultivation.

Methane emissions from enteric fermentation in ruminant animals accounted for one-quarter (SY) to half (EY) of climate impacts in the FND scenarios. To reduce these emissions, feed supplementation with red seaweed has shown promising results (Roque *et al.* 2021; Nilsson & Martin 2022), and could potentially alleviate some of the trade-off between cropland use and GHG emissions observed in the FND scenarios.

Cropland demand in deforestation-prone regions in the EU-S scenarios

Reduced EU soybean imports in the EU-S scenarios led to reduced demand for cropland in South America in all scenarios, while demand for cropland in Southeast Asia for palm oil production increased, except in the OIL-scenario (**Figure 11a**). In absolute terms, the increased cropland demand in Southeast Asia was small (0–2 Mha) compared with the reduced demand in South America (9–12 Mha), but there is nonetheless a risk of shifting impacts from one region to another. This trade-off is analysed in **Figure 11b**. The results show that all scenarios avoided carbon dioxide emissions of 17–27 Mt CO_2, but that the large biodiversity impacts associated with palm oil production in Southeast Asia resulted in a net loss of regional species in both the FEED and FOOD scenarios (4.8–18 species). In the OIL scenario, this trade-off was avoided by using all EU cropland spared from feed cultivation for rapeseed oil production, thus avoiding increased palm oil demand. It

[5]Based on data underlying Moberg *et al.* (2021)

should be noted that the changes in cropland demand following from the EU-S scenarios are large, corresponding to up to nine and three years of historical soybean and palm oil area increases, respectively (**Figure 11a**). Considering this, it can be questioned if it is reasonable to assume that land-use change factors derived from historical data can be linearly extrapolated, as was the case in the analysis presented in **Figure 11b**. Actual impacts on forest carbon stocks and biodiversity would be affected by factors such as whether reduced cropland demand involves avoided future deforestation or afforestation of previously deforested areas, which has implications for both time scales and resulting carbon stocks and biodiversity (Martin *et al.* 2013; Moreno-Mateos *et al.* 2017). Global markets would also respond to changes in EU demand for soybean meal and vegetable oils, so actual changes in cropland demand would deviate from results presented here. Nonetheless, this analysis shows a potential trade-off in reducing the use of soybean meal in animal feeding that needs to be accounted for, especially under increased global demand for fat (as discussed in section 5.1.1).

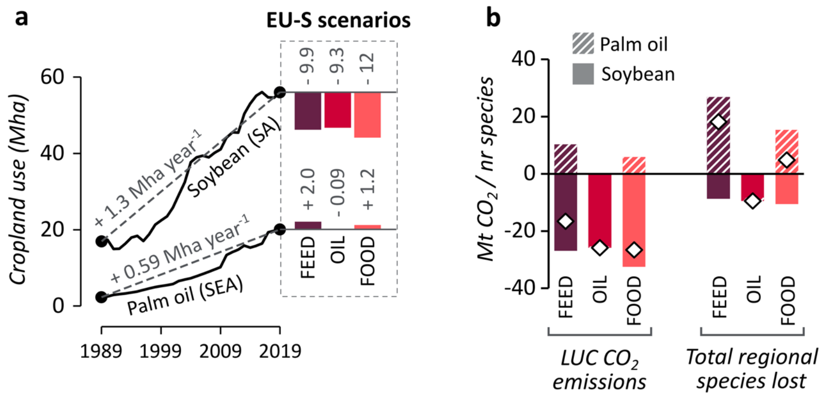

Figure 11. a) Change in soybean area in Argentina, Brazil and Paraguay (South America; SA) and oil palm area in Indonesia, Malaysia and Papua New Guinea (Southeast Asia; SEA) from 1989 to 2019 (FAO 2022), together with net changes in area demand following the different EU-S scenarios. **b)** Changes in land use change (LUC) CO_2 emissions and total regional species lost due to changed demand for soybean (solid fill) and palm oil (white hatch) in the different scenarios (diamonds indicate net impacts). Impacts were estimated using changes in demand in the different scenarios compared with the baseline, together with product- and country-specific LUC factors from Henders *et al.* (2015) for CO_2 emissions and from Chaudhary and Kastner (2016) for regional species lost.

5.2 Livestock as landscape managers
– *Ecosystem services across Swedish farms*

Analysis of the non-provisioning ecosystem services indicator suite in **Paper IV** showed that farms specialising in ruminants and horses and mixed farms had more varied landscapes (small to moderate effects; **Figure 12a**), semi-natural grasslands (large effects; **Figure 12b**) and small-scale habitats (negligible to small effects; **Figure 12c**) and better crop sequences (small to moderate effects; **Figure 12d**) compared with surrounding farms specialising in crop production. Small-scale farms had more varied landscapes (moderate effect) and small-scale habitats (small effect) and better crop sequences (small effect). Farms specialising in monogastric livestock, on the other hand, were associated with less varied landscapes (small effect) and inferior crop sequences (small effect) compared with surrounding crop production farms.

Results from the generalised additive model (GAM) for landscape variation (**Paper IV**) showed that smaller farm size gave the strongest response in the model. Similar associations between farm size and landscape variation/heterogeneity or field size (which correlates with landscape variation; **Paper IV, SM**) have been reported previously by others (*e.g.* Levin 2006; Belfrage *et al.* 2015). Differences in farm size across farm types may therefore partly explain the observed differences in landscape variation (**Figure 12a**). However, after controlling for the effects of farm size, livestock densities of ruminants and horses still gave a positive response in the GAM, while density of monogastric animals gave a negative response, confirming the patterns seen in **Figure 12a**. An important incentive for making fields larger and more rational is to minimise time spent on machine operations per hectare, in order to reduce costs (Clough *et al.* 2020). A potential explanation for the observed association between ruminants and horses and landscape variation may therefore be the higher share of ley cultivation on these farms. Ley needs fewer field operations than arable crops and thus gives a smaller incentive for field rationalisation (Wästfelt & Eriksson 2017). Wästfelt and Eriksson (2017) also noted that field size had increased more on farms specialising in cereal production than on those specialising in ruminant enterprises between 1990 and 2014. In the entire farm sample analysed in **Paper IV**, ley was cultivated on 46% of cropland and 7% was in fallow. The corresponding values for only the smallest fields (less than one hectare) were 73% in ley and 15% in fallow. This further strengthens the hypothesis that ley cultivation permits smaller fields to be kept in production.

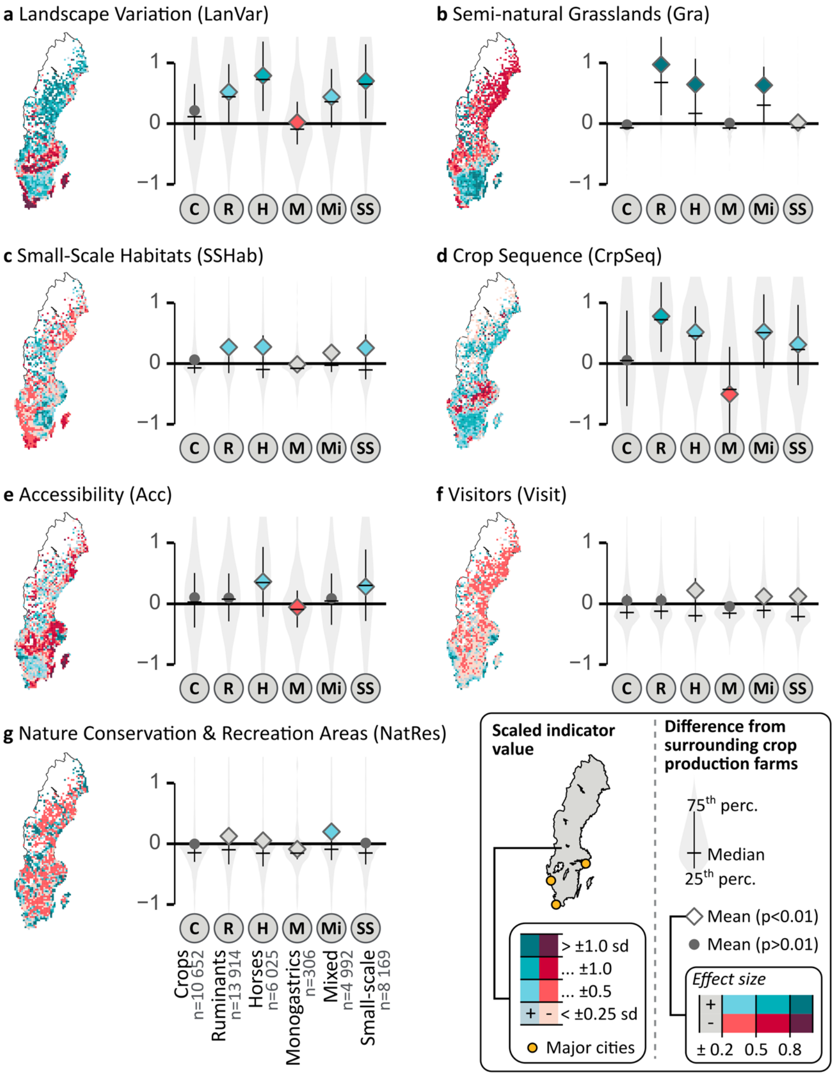

Figure 12. Maps showing regional patterns in scaled indicator values on a 15 km x 15 km grid. Colour of each grid cell reflects the area-weighted mean value of farms within that grid cell. Plots show the difference in scaled indicator values from the area-weighted mean value of crop production farms within a 20-km radius. Diamonds indicate a statistically significant difference in mean difference from the 'Crops' group (Welch's t-test; p<0.01) and colour effect size (Cohen's d).

While positive associations were found between ruminant animals and several of the ecosystem services indicators, increased livestock density beyond around one livestock unit per hectare for cattle and 0.5 for sheep and horses did not seem to increase indicator scores. This was observed both in the GAM for landscape variation and for semi-natural grasslands and crop sequences when comparing clusters of farms with varying livestock density (**Paper IV**).

The results for indicators relating mainly to cultural ecosystem services were less conclusive. Horse farms and small-scale farms were more accessible (small effects; **Figure 12e**) and horse farms also tended to receive more visitors than surrounding crop production farms, but here effect size was negligible (**Figure 12f**). For nature conservation and recreation, only mixed farms differed from surrounding crop production farms with a non-negligible effect size (small effect; **Figure 12g**). For visitors there were clear geographical patterns, with farms closer to the major Swedish cities and along the coasts receiving more visitors (**Figure 12f**). This may suggest that closeness to people is more important than other qualities in determining visitation frequency on farms, as has previously been suggested by de Vries and de Boer (2008). However, the indicator for visitors correlated with both semi-natural grasslands and nature conservation and recreation areas (**Paper IV**), indicating that landscape qualities other than closeness to people also matter. Calculating the number of visitors for different land uses also showed that semi-natural grasslands received more visitors per hectare than any other agricultural land use (**Paper IV**).

It is interesting to note that horse farms performed well across all indicators analysed here. This is a category of farms that has received little scientific attention but which, based on the results presented here, seems to make an important contribution to non-provisioning ecosystem services from agricultural landscapes. Grazing horses have previously been shown to preserve biodiversity values, including pollinator habitats in semi-natural grasslands (Köhler *et al.* 2016; Saastamoinen *et al.* 2017; Garrido *et al.* 2019), and could potentially do so while emitting less methane compared with grazing ruminants. However, it is important to note that in order to preserve site-specific plant and animal communities in semi-natural grasslands, the historical management regime under which these ecosystems have developed (often haymaking or grazing by cattle and sheep) should ideally be mimicked in future management (Bonari *et al.* 2017).

6. General discussion and perspectives

In this chapter, a general discussion is provided and suggestions for future research are put forward. The focal point is the livestock on leftovers concept and how it relates to both the role of livestock as resource users and landscape managers. The advantages and disadvantages of this concept and associated modelling techniques in guiding food system actors are also discussed.

6.1 Prospects and challenges with livestock on leftovers

The livestock on leftovers concept explored in this thesis is one among many ways to think about the future of livestock. Most agree that environmental impacts and resource use in livestock production need to be reduced substantially in order to feed a growing human population within planetary boundaries, but there is less agreement on the route towards that end (Garnett 2015). This includes the relative importance attributed to supply-side versus demand-side measures and the confidence in future technical developments. In a report entitled *Gut Feelings And Possible Tomorrows*, Garnett (2015) sketches out a number of livestock futures. These range from a 'calibrated carnivory' future, where demand is viewed as exogenous and the livestock sector needs to rely on technological land-winnings to meet this demand, while minimising impacts per unit produced, to a 'fruits of the earth' future, where strong demand-side policies need to be implemented to push consumption from resource-intensive and unhealthy animal-source foods towards mainly plant-based diets, produced in innovative and optimised production systems.

The livestock on leftovers concept is somewhere in the middle, with less emphasis on technological developments. The appeal with this narrative compared with other futures is that it inherently integrates the supply and demand side and thereby favours systems thinking, where accounting for interconnections within food systems is important. Throughout the work in this thesis, speaking to different stakeholders, it also emerged as a narrative that can appeal to diverse actors, ranging from livestock farmers to environmental NGOs, and may thus favour constructive discussion. That said, there are a number of challenges. First, the concept relies on transformative changes in the food system, and is thereby more useful in the policy arena for envisioning possible futures, than in providing concrete decision support to producers or consumers today. For example, a producer increasing the share of by-products in their feed mix would only reduce total land use if the by-products introduced are currently under-utilised or if accompanied by simultaneous consumption changes. Likewise, a consumer adopting a diet compatible with a livestock on leftovers scenario to reduce their resource use or environmental impacts may not achieve the desired effect, as this would rely on simultaneous changes in production systems and animal diets.

Second, a fundamental assumption in the livestock on leftovers concept is that the highest utility of biomass is for food production. This implies that food is in short supply, while *e.g.* bioenergy or biomaterials are not, or at least that food production should always be the top priority. For example, in the FND scenarios it was shown that using all ley biomass generated in the organic production systems for animal-source food production could provide more people with diets containing more animal-source food, while bioenergy production was only assumed to cover energy demand in the agriculture sector. An alternative could have been to use ley biomass for energy to replace fossil fuels in other parts of society. The IPCC *Special Report on Climate Change and Land* states that *"mitigation response options that limit warming to 1.5 or 2°C would require conversion of large areas of land for […] bioenergy crops"* and that *"pathways that minimise land use for bioenergy […] are characterised by rapid and early reduction of GHG emissions in all sectors"* (Shukla *et al.* 2019, p. 49). Thus depending on how the future energy system develops, agricultural biomass may be increasingly needed for non-food purposes to reach climate targets. In a Nordic context, Börjesson (2016) included *e.g.* crop residues, food waste and surplus ley cultivation as potential sources for future bioenergy production in Sweden. To provide policy guidance on how to prioritise leftover resources between livestock and other uses, the livestock on leftovers concept would need to be integrated with assessments of the energy system and other potential uses of agricultural biomass.

Finally, defining the resources that can be considered leftovers not in competition with direct plant-source food production is not straightforward, as discussed further in the following sections.

6.2 Challenges in defining leftover resources

6.2.1 Land use leftovers

From a resource user perspective

Most previous studies presenting scenarios with 'livestock on leftovers' have assumed that land use leftovers comprise areas defined as 'grasslands' or 'permanent grasslands' in statistics (*e.g.* Schader *et al.* 2015; Röös *et al.* 2017a) or according to other data sources (*e.g.* van Hal *et al.* 2019). However, the extent to which food crop cultivation is actually unfeasible on these areas is uncertain. As previously mentioned, around one-third of permanent grasslands globally are estimated to be potentially convertible to cropland (Mottet *et al.* 2017). In a European context, Nitsch *et al.* (2012) found that land use changes between 2005-2007 in Germany resulted in both large-scale conversion of permanent grasslands to croplands, and *vice versa*, and even larger areas of grasslands being removed from and (re)introduced to agricultural production. This shows that the area currently in permanent grassland is not necessarily a good proxy of its unsuitability for direct plant-source food production, and that land use is rather an economic decision than a decision based solely on the land's biophysical suitability for a certain purpose. An alternative approach may be to use modelled land suitability indices, as done by van Zanten *et al.* (2016b) in calculating the ratio of animal protein to plant protein production possible on a certain piece of land to assess whether a certain livestock production system provides a net benefit to food supply or not. However, such calculations will always depend on assumptions on the level of labour and other inputs applied to the soils, which affect the potential yields. As such, economic and political aspects such as price of land, labour, fertiliser and food, together with agricultural support and other policy instruments, affect the areas considered marginal for food crop production, but useable for grazing or other means of harvesting fodder for livestock. It is therefore difficult to find objective biophysical definitions of land use leftovers for use in scenario studies.

From a landscape manager perspective

Apart from acting as a resource for food production, permanent grasslands are also important habitats supporting biodiversity and several ecosystem services (Bengtsson *et al.* 2019). There is thus an argument for maintaining areas in permanent grassland beyond the perspective of food production alone. Therefore, a more useful definition of land use leftovers may be found by integrating a 'landscape manager' perspective, rather than trying to derive a definition strictly from the resource use perspective. This has also been highlighted in previous livestock on leftovers scenario studies. For example, Röös *et al.* (2016) included that *"Semi-natural pastures [should be] grazed by animals on the grounds of biodiversity preservation"* (p. 3) as a key principle in their scenarios, and Schader *et al.* (2015) state that *"grasslands can contain large carbon stocks and can provide many ecosystem functions [...] much of which would be lost if grassland were converted to arable land"* (p. 9). In the FND scenarios, this second function of grasslands was acknowledged, and land use leftovers were defined as semi-natural grasslands and Norwegian forest/alpine pastures (the latter only in EY scenario), which are important habitats for biodiversity conservation (Eide 2014) and culturally embedded in farming traditions (Eriksson & Cousins 2014; Tunon *et al.* 2014).

According to the Swedish farm register data used in **Paper IV**, there were 1.2 million grass-eating livestock units[6] in Sweden in 2016. Half of these were on farms with less than 6.0 livestock units per hectare semi-natural grassland, which accounted for 93% of the total semi-natural grassland area (**Figure 13**). The remaining half of all livestock units thus make a very small contribution to management of semi-natural grasslands, which indicates that much fewer animals would theoretically be needed to graze these areas and preserve associated values. It should be noted, however, that 17% of the semi-natural grassland area in 2016 was on farms not reporting any grass-eating livestock. A small share of these areas may comprise hay meadows managed purely for biodiversity conservation, but the majority are likely managed by animals from other farms or horses not captured in the Swedish farm register (less than one-third of all horses are represented in the Swedish

[6]Livestock units in cattle, sheep and horses.

farm register; Swedish Board of Agriculture 2017). Animals found on one farm may therefore contribute to managing grasslands on other farms. It can also be noted that while the area of semi-natural grasslands found on farms specialising in beef is almost twice that of farms specialising in dairy, Spörndly and Glimskär (2018) found that animals of dairy and beef breeds are equally common in grazing semi-natural grasslands. This indicate that dairy farms are important in supplying young animals to specialised beef farms where grazing occurs.

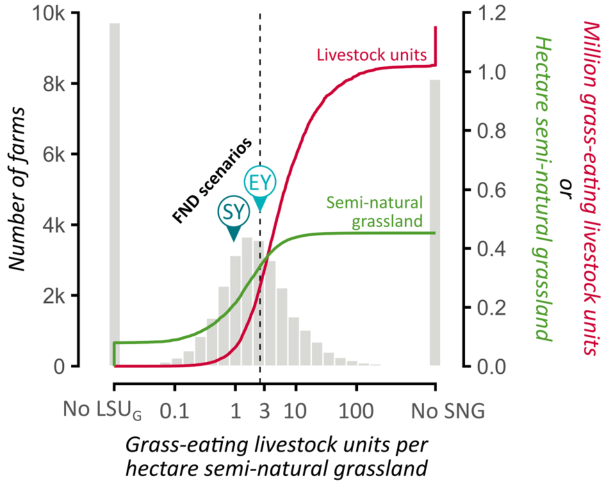

Figure 13. Distribution of grass-eating livestock units (*i.e.* cattle, sheep and horses; LSU_G) per hectare semi-natural grassland (SNG) in the sample of Swedish farms from **Paper IV**. Solid lines show cumulative livestock units and semi-natural pasture area and the vertical dashed line shows the value for Sweden as a whole (2.6 LSU_G/ha). The number of livestock units per hectare semi-natural grassland in the FND-SY (0.9 LSU_G/ha) and EY (2.6 LSU_G/ha) scenarios is also indicated.

The management of semi-natural grasslands thus arises in a system where farms are interconnected and, based on the data used here, it is difficult to determine which animals contribute to grazing and which do not. In the FND-SY scenario, it was found that 420 000 ruminant livestock units (less than half the current herd) would be able to graze all semi-natural grasslands in Sweden. However, this relies on animals being perfectly distributed across Sweden according to where semi-natural grasslands are located, which may be difficult to achieve in practice as pastures are often small and scattered (Holmström *et al.* 2018). There are currently enough animals within 15 km from 95% of Swedish semi-natural grasslands for these grasslands to be grazed (Larsson *et al.* 2020). However, managing all semi-natural grasslands with fewer animals would rely on animals being distributed over a large number of small farms, each with few animals, or accepting long animal transport to pastures. It should also be noted that the majority of Swedish grassland biomes have poor conservation status (Eide 2014) and that the area of semi-natural grasslands would need to increase to rectify this (Wallander *et al.* 2019), relying on more animals grazing.

Future research should aim to identify grassland areas where management through grazing or mowing is needed for biodiversity conservation and supply of important non-provisioning ecosystem services. This would need to be done in a regionalised manner and should include areas that currently exhibit sought values as well as areas where restoration and management efforts could be implemented to (re)create these values. Such analyses could serve as inputs to quantify the availability of land use leftovers from a landscape manager perspective and identify livestock systems that can deliver grassland values while minimising resource use and environmental impacts.

6.2.2 Cropping system leftovers

The term 'cropping system leftovers' was introduced in **Paper II** in order to account explicitly for the need for grass-legume leys in organic crop rotations. In the FND scenarios, more than 90% of nitrogen fixation occurred in grass-legume leys, despite strong increases in cultivation of grain legumes for human consumption. More grain legumes could potentially be included in the scenarios. However, considering the agronomic difficulties in frequent cultivation of grain legumes (Röös *et al.* 2018a), especially in organic farming, adequate nitrogen supply would likely need to rely mainly on forage legumes in the absence of synthetic nitrogen fertilisers. This shows that cropping systems relying on biological nitrogen fixation are likely to generate considerable cropping system leftovers in the form of forage crops that need to be accounted for when assessing the potential for livestock production based on leftover biomass. While ley cultivation is especially important in organic cropping systems, crop rotations including perennial leys are also beneficial for conventional cropping systems and can reduce the need for external inputs (Albizua *et al.* 2015).

In the FND scenarios, livestock production was assumed to be well integrated with crop production. Ley was grown in rotation with other crops to limit pests and weeds and provide nitrogen to succeeding crops. The importance of these ecosystem services in the organic cropping system warranted consideration of ley biomass as a cropping system leftover available for animal feeding. The extent to which this is true also for leys currently cultivated in the Nordic region is an open question.

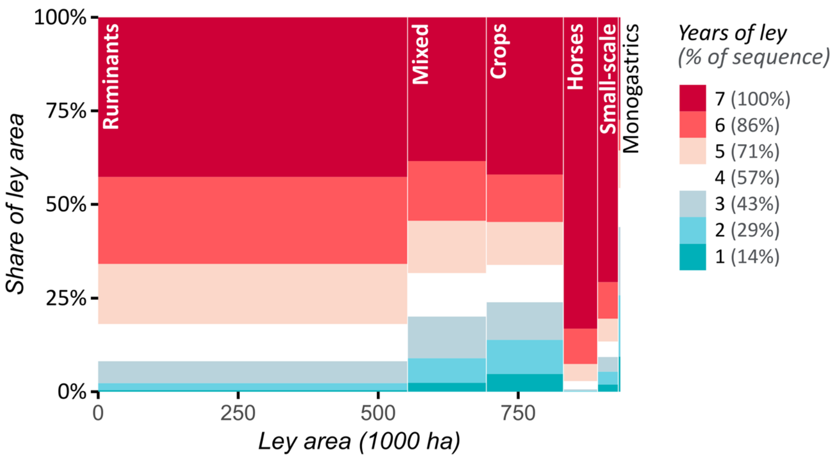

Figure 14. Area of ley on different farm types (x-axis) and share of ley area (y-axis) in crop sequences including between one and seven years of ley (colour) in the seven-year crop sequence from 2013–2019. The area of each rectangle is proportional to the total area of ley within that combination of farm type and ley cultivation frequency.

Analysis of the crop sequences from **Paper IV** revealed that only 12% of the ley area in Sweden was in crop sequences where ley is grown for one to three years in the seven-year sequences 2013–2019 (**Figure 14**). These leys may be considered cropping system leftovers if they are in rotation with crops destined for direct human consumption. On the other hand, 46% of the ley area cultivated was not in rotation with any other crops. A large share of the ley currently cultivated in Sweden is thus not well integrated into a cropping system. However, some ecosystem services may still be supplied by these leys. For example, nitrogen fixation may contribute to nitrogen supply for other crops through livestock manure, although the share of leguminous species in leys usually drops over time, especially if fertilised. Based on the data it is not possible to know the share of legumes in these leys and if they are frequently re-established or otherwise managed to maintain a high share of legumes. Carbon sequestration is another ecosystem service associated with ley cultivation that does not depend on ley being in rotation with other crops. But, the soil-improving aspects of this become less strong, and other land uses such as bioenergy production with short rotation coppice would likely sequester more carbon (Hammar *et al.* 2014). Overall, much of the current ley area in Sweden cannot be considered a cropping system leftover, as its contribution to the cultivation of food crops is likely limited.

Some of the area with permanent leys may however have a quite low potential for food crop cultivation, especially in northern Sweden, and if left unploughed and unfertilised and with proper management they may develop high biodiversity values, especially on calcareous soils[7]. Extensively managed permanent leys may therefore be important areas to target if aiming to increase the area of semi-natural grassland in Sweden (Bengtsson & Claesson 2018). So, while leys that are not in rotation with other crops cannot be considered cropping system leftovers, some may be considered land use leftovers, as discussed in section 6.2.1.

6.2.3 By-products and wastes

In the FND scenarios, by-products and wastes considered for livestock feeding were (gross energy [PJ] in brackets) rapeseed cake (21), cereal husks and bran (7.0–7.6), bakery waste (3.8–4.1), sugar beet pulp and molasses (3.1–3.7), brewer's grain (2.4–2.8), fishmeal from fish cleaning (1.4–1.6) and low-grade potatoes (1.1–1.3) and roots (0.4). These feeds are all recovered to varying degrees and used for feed today, but this does not represent an exhaustive list of potential by-products and wastes available for livestock feeding. On a global level, Sandström *et al.* (2021) found large untapped theoretical availability of crop residues (*e.g.* straw and sugarcane tops) and livestock by-products (*e.g.* blood and feather meal).

In the FND scenarios, crop residues in the form of straw was only considered for bedding and bioenergy. Other crop residues that could be considered are *e.g.* leaves from sugar beet crops and other roots for use as fodder for ruminant animals, although high inclusion rates in animal diets may cause health problems (Gauffin & Spörndly 1992). Sandström *et al.* (2021) also found that only around 14% of the theoretical availability of crop

[7]Olle Kvarnbäck, agronomist and biologist, specialist in biodiversity of the agricultural landscape, personal e-mail correspondence on 23 February 2022

residues could be used to replace food-competing feeds in animal diets due to the low nutritional qualities of these feeds. Removing crop residues from arable land also represents an additional removal of nutrients and carbon that needs to be considered. Regarding animal by-products, only fishmeal from cleaning was considered in the FND scenarios. Current EU legislation restricts the use of animal by-products in livestock feeding, by prohibiting use of ruminant animal by-products and intra-species feeding to avoid transmission of pathogens (Sandström *et al.* 2021). Nonetheless, Sandström *et al.* (2021) found a potential to increase the use of livestock by-products in animal feeding almost five-fold, while still leaving a large share of the theoretical availability for other uses, thereby potentially avoiding competition with bioenergy and direct food uses (Bajželj *et al.* 2021). Whey is a protein-rich by-product from the dairy industry that is used in animal feeding but is also frequently used in the food industry, so in the FND scenarios it was assumed that whey would be used only for direct food purposes.

Consumer food waste was only considered for bioenergy production through anaerobic digestion in the FND scenarios. Other studies have shown potential to incorporate food waste in *e.g.* pig diets in particular (van Hal *et al.* 2019). While feeding pigs food waste has been shown to carry a lower environmental impact than other disposal options if it replaces conventional pig feed, the use of mixed food waste in animal feeding is currently prohibited in the EU for fear of disease transmission (Salemdeeb *et al.* 2017). Processing of food waste could mitigate these risks. Black soldier fly larvae composting has shown promising results for valorising both food waste and human faeces into a protein-rich animal feed (Lalander *et al.* 2019). It also generates a compost that can be applied to soils.

In the FND scenarios, low-grade potatoes and roots were considered a by-product available for animal feeding, while all cereals grown were assumed to be used for direct food purposes. This is not always the case at the present time, as cereals intended for direct human consumption, but failing to meet quality standards, may be reverted to feed use. These low-grade cereals could thus be considered a by-product of food cereal production available for animal feeding without competing with food production. However, Tillgren (2021) found that large quantities of cereals used for feed in Sweden meet food-grade quality standards and that the quality standards could be lowered for many food purposes. This implies that the amount of cereals that can be considered a leftover from food cereal production in Sweden is low.

Future research should build on previous efforts to identify leftover resources that are currently underutilised, but which could be used to replace food-competing feeds in livestock diets, and develop techniques to do so safely. On the other hand, many resources considered leftovers in the FND scenarios and other livestock on leftovers studies may have direct food uses. For example, developments in food processing can enable the use of rapeseed meal in the food industry (Östbring *et al.* 2020) and, as previously discussed, more whole grain cereals are promoted in human diets for health reasons (Willett *et al.* 2019), which would reduce the availability of husks and brans as a by-product available for animals. Moreover, insects reared on organic wastes, discussed above as a potential protein feed, may also be considered for direct human consumption (Parodi *et al.* 2018). This shows that defining by-products as not suitable for direct human consumption (a key criterion for defining a by-product as a leftover resource) is not straightforward and may change with developments in food processing and consumer tastes.

Finally, it is important to note that increased use of by-products or other leftover resources as animal feed only benefits the resource use efficiency of food systems if other food-competing feeds are replaced and not in cases where the utilisation of a leftover depends on a simultaneous increase in the use of food-competing feeds.

6.3 Modelling food systems

The FND and EU-S scenarios were modelled using biophysical food system models, in which material flows are tracked within the system to generate biophysically feasible and internally consistent scenarios of the future (Erb *et al.* 2016; Muller *et al.* 2017). Such models can provide valuable policy insights, as they connect the supply and demand side, making interconnections visible. As an example, in **Figure 15** cropland use per animal-source protein is plotted against total animal-source protein production in the FND and EU-S scenarios. The diagram reveals that as animal-source food production increases, land use per unit produced also increases. This is an effect of the limited availability of land use leftovers and by-product feeds. As the total volume of animal-source food production increases, more feeds directly sourced from croplands need to be incorporated into livestock rations, thereby increasing cropland demand per unit product. However, as the ley biomass used for livestock feeding in the FND scenarios was considered a cropping system leftover (*i.e.* needed for feasible organic crop rotations), it is not self-evident that this cropland use should be allocated to animal-source food production. If land used for cropping system leftovers are instead allocated to both animal- and plant-source food, based on their respective contribution to protein in the final diets, cropland use per unit animal-source protein decreased when animal-source protein in the diets increased, reflecting the overall improved land use efficiency in the EY compared with SY scenario (**Figure 15**).

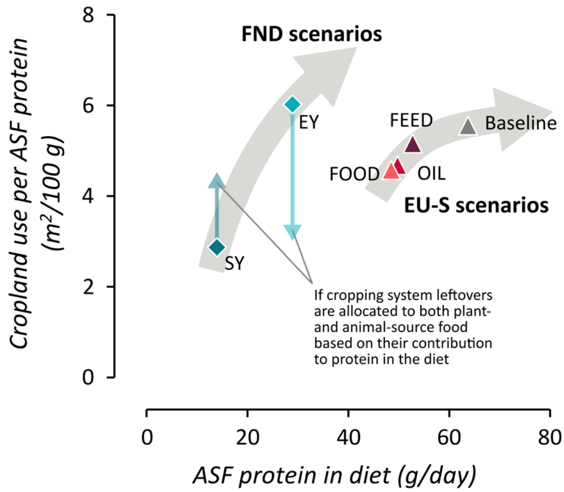

Figure 15. Cropland use per gram edible protein in animal-source food (ASF) as a function of animal protein in diets. No land use is allocated to the use of land use leftovers (*i.e.* semi-natural or permanent grasslands) and by-products. For the FND scenarios, cropping system leftovers used for feed are allocated to the animal-source foods, but arrows indicate the results if cropping system leftovers are instead allocated to both plant- and animal-source foods based on their respective contribution to human-edible protein in the diets.

Another common modelling technique used to assess consequences of dietary shifts is to employ fixed factors for land use and environmental impacts per unit product (often based on life cycle assessments) in order to assess different dietary patterns (as in *e.g.* Tilman & Clark 2014; Röös *et al.* 2015; Poore & Nemecek 2018). Because such methods fail to account for potential changes in feed rations with changes in absolute volumes of animal-source food production, they risk underestimating impacts of dietary changes on land use. These aspects have previously been discussed by *e.g.* Frehner (2021), who also noted that using consumption-oriented approaches with fixed impact factors may result in inconsistent scenario formulations by *e.g.* failing to account for the connection between milk and meat production in dairy production systems. Methods accounting for food system-interconnections also allow for identification of system dynamics in the interface between production and consumption, such as the observation that fat supply limited productivity in the FND scenarios and the dependence on imported soybean meal to utilise silage maize in the EU-S scenarios.

In studies aiming to assess transformative changes in food consumption, and therefore production, methods and models capable of accounting for different food system-interlinkages are therefore crucial. That said, fixed impact factors may be 'good-enough' proxies of food system consequences when dietary changes are relatively small. For example, in Moberg *et al.* (2021) fixed factors were used to assess the impacts of implementing a climate tax on food across a suite of impact categories.

While the models used in the FND and EU-S scenarios were flexible in terms of animal feed rations, they assumed fixed productivity levels of the animals. For the FND scenarios, lower productivity was assumed *a priori* in order to reflect organic practices and enable better use of grazing resources, while in the EU-S scenarios productivity was assumed to be unchanged compared with the baseline. As animals with lower productivity have been shown to be better suited to utilising lower-quality feeds (van Hal *et al.* 2019), implementing such flexibility in the models might have allowed for better utilisation of leftovers in terms of supplying animal protein in the scenarios.

The biophysical food system models used here account for different food system-interlinkages to generate biophysically feasible scenarios for the future, but they do not account for any socio-economic consequences or constraints. These models are therefore capable of providing possible option spaces for the future, helping policymakers in envisioning possible futures and identifying trade-offs. They are however not capable of predicting consequences of certain decisions or changes. To assess consequences of *e.g.* political decisions or societal developments and trends, biophysical models need to be integrated with models of socio-economic dynamics. However, these types of models, which are generally referred to as integrated assessment models (IAM), have been criticised for lack of transparency in model structures, reducing the credibility of derived results (Rosen 2015). In this context, simpler and more transparent models based on purely biophysical relationships (as used in this thesis) can provide important reality checks for more complex models integrating socio-economic dynamics (Erb *et al.* 2016).

6.4 The interface between livestock as resource users and landscape managers

In this thesis, two perspectives on livestock were scrutinised. In the first perspective, *livestock as resource users*, livestock's role is to supply nutritious food while avoiding competition for resources that could be used more efficiently for plant-source food production. In the second perspective, *livestock as landscape managers*, livestock's role is to manage agricultural landscapes and facilitate biodiversity conservation and the supply of non-provisioning ecosystem services. These two perspectives may lead to different views on the role of livestock in future food systems. At the same time, there is a large interface between the two perspectives and they may complement one another. For example, as discussed in section 6.2.1, a landscape manager perspective may be more fruitful than a strict resource use perspective in defining grassland areas where livestock production is the best option. In addition, in **Paper IV** farms specialising in ruminants performed better than crop production farms across a number of indicators for non-provisioning ecosystem services. While the mechanism behind these differences and the extent to which a reduced number of livestock would involve loss of ecosystem services are not clear, they show important potential trade-offs in reducing the environmental and resource use impacts of food through reduced animal-source food consumption, a finding that would be missed if applying only a resource use perspective. Future research should aim to integrate these perspectives (also including socio-economic perspectives not covered within this thesis), to provide a clearer picture of the role of livestock in food systems and ultimately guide policymakers and other actors in the challenging task of balancing livestock's positive contributions against the urgent need to reduce their negative impacts.

Based on this work, such a balance may be achieved by facilitating the shift towards more plant-based diets that reduce food-feed competition and pressure to bring new land into agricultural production, while at the same time providing incentives for livestock farmers to use leftover resources and manage agricultural landscapes for increased biodiversity and ecosystem services. The latter could include better incentives to graze semi-natural grasslands and keep small fields in production, as well as to integrate ley in crop rotations with food crops.

7. Conclusions

A typology of leftovers resources available for livestock feeding without causing food-feed competition was proposed. Leftovers were subdivided into *land use leftovers*, *cropping system leftovers* and *by-products and wastes*.

Land use leftovers are difficult to define from a strict resource use perspective (*i.e.* as land where direct plant-source food production is unfeasible). An alternative/complement is to define land use leftovers from a landscape management perspective as areas where livestock contribute to biodiversity conservation and important non-provisioning ecosystem services. *Cropping system leftovers* is a novel concept that accounts for the potential benefits of forage crops in crop rotations. The results showed that it is important to account for these, especially in scenarios of reduced reliance on external inputs in agriculture. The quantity of *by-products and wastes* available as leftover resources depend on assumptions on what is desired for human consumption, which may change with developments in food processing and dietary preferences. For all leftover resources, alternative non-food uses such as for nature conservation and bioenergy are important to consider.

Ruminants were favoured over pigs and poultry under both a *livestock as resource users* and *livestock as landscape managers* perspective.

Optimising livestock production for maximum food supply favoured ruminants in both scenarios of an organic and regionalised Nordic food system where livestock were limited to leftover resources (the FND scenarios), and in scenarios where soybean feed imports into the EU were ceased (the EU-S scenarios), mainly due to the high availability of grass and other roughages only suitable for ruminant animals. Analysis of non-provisioning ecosystem services on Swedish farms showed that farms specialising in ruminants (and horses) performed better for several of the ecosystem services indicators analysed compared with surrounding farms specialising in crop production.

When livestock were limited to leftovers in the FND scenarios, organic farming in the Nordic countries was able to support a population of up to 37 million (30% more than its projected 2030 population).

In this situation, animal-source food contributed up to 29 g protein cap^{-1} day^{-1}, equivalent to around half the current protein intake in animal-source foods. Compared with current diets, both nutritional benefits and challenges were observed, and greenhouse gas emissions would be substantially reduced. Soil nutrient balances showed deficits of both nitrogen and phosphorus in the scenarios, so even under optimistic assumptions of nutrient circularity other external sources would likely be needed.

Ceased EU soybean feed imports without encroaching on EU cropland currently used for other purposes relied on at least a 17% reduction in the supply of animal protein in the EU-S scenarios.

This considerably reduced cropland demand in deforestation-prone regions, but shifted demand from South America (soybean) to Southeast Asia (palm oil) in two out of three scenarios, with a potentially negative net effect on biodiversity. Increasing EU vegetable oil production could avoid this trade-off. Reduced consumption of animal-source food in line with the scenarios would likely have limited negative impacts on macro- and micronutrient intake if appropriately replaced with plant-source foods. Ruminant feed rations changed to include less maize silage in the scenarios, which shows that the increasingly common maize silage-based rations are dependent on protein-rich feeds such as soybean meal.

Swedish farms specialising in ruminant animal production had more varied landscapes (small effect), semi-natural grasslands (large effect) and small-scale habitats (small effect) and better crop sequences (moderate effect) than nearby farms specialising in crop production.

Farms specialising in pigs or poultry were not associated with a higher score on any of the ecosystem services indicators analysed. Variation across individual farms was large and higher livestock density (above approximately one livestock unit per hectare) was not associated with higher scores for the indicators.

Swedish semi-natural grasslands attracted more visitors and were to a larger extent located within designated nature conservation and recreation areas compared with other agricultural land uses.

This adds to previous findings on the importance of semi-natural grasslands in providing cultural ecosystem services.

Adequate fat supply to diets was found to limit the production system in the FND scenarios, and the majority of cropland needed to compensate for reduced supply of animal-source foods and soybean oil (associated with reduced soybean meal use) could be attributed to fat production in the EU-S scenarios.

While protein is often the focal point when considering reduced consumption of animal-source foods, the results presented here shows that it is also important to account for fat supply, especially considering agronomic challenges with plant-based fat production and competition from bioenergy and other non-food uses.

There is a potential trade-off in efficient use of leftover resources for food production and greenhouse gas mitigation.

When more ruminants were included in the FND scenarios, available leftovers could be utilised more efficiently, which reduced per capita cropland demand. However, more ruminants also led to higher per capita greenhouse gas emissions due to increased methane emissions.

It is important to account for food system interlinkages and resource constraints when assessing large-scale changes in animal-source food consumption.

Results from both the FND and EU-S scenarios showed that cropland use per unit of animal-source food produced changed with total animal-source food production. Lower animal-source food production allowed for a larger share of animal feed to consist of by-products and other leftover resources, and thus lower cropland requirement per unit produced. Failure to account for this effect may lead to underestimation of land use impacts from changed animal-source food consumption.

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Popular science summary

The public debate on the role of livestock in future sustainable food systems is lively and often polarised. It is becoming increasingly clear that animal-source food consumption need to decrease in high-income settings to limit environmental impacts and reach climate targets. In addition, livestock currently eat large quantities of cereals and other grains that can be used directly for food – almost half of all cereals grown in the European Union (EU) are fed to animals. Using these for direct human consumption could allow more people to be fed per area of land. However, livestock may also contribute to food system sustainability in various ways. In the debate, it is often emphasised that livestock play a key role in making use of resources that would otherwise not be available for food production. The term 'leftover resources' can be used to describe these resources, which include grasslands where crop production is not feasible or different forms of by-products and wastes that are not desired for direct human consumption. Moreover, livestock may contribute to biodiversity conservation and ecosystem services, for example by grazing semi-natural grasslands or by providing an incentive to include perennial grasses and legumes (known as ley) in crop rotations, which can improve the soil, fix nitrogen from the air and limit pests and weeds. This is especially important in organic farming, but is also beneficial in conventional agriculture. The aim of this thesis was to inform the debate by providing quantitative evidence for these arguments.

Two sets of scenarios were explored in this thesis. The first set described a future food vision for the Nordic countries Denmark, Finland, Norway and Sweden in which the majority of food consumed was produced within the Nordic region using organic farming and livestock limited to using only leftover resources. These scenarios represents a drastic change compared with current food systems. Therefore, the second set of scenarios explored a potential first step in reducing the use of feeds that can be used directly for food by assuming that all soybean feed imports into the EU would be stopped.

Finally, the role of livestock in shaping agricultural landscapes that contribute to ecosystem services other than food production was explored by studying the association between the presence of livestock on a farm and different indicators for ecosystem services.

In the following paragraphs, some of the key results of this work are highlighted and explained.

When livestock were limited to leftovers, organic farming in the Nordic countries was able to support a population of up to 37 million (30% more than its projected 2030 population).

In this situation, meat consumption was reduced from seven to around one weekly serving and total animal protein consumption was at least halved. No mineral fertilisers were allowed in the scenarios, but the results showed that optimistic assumptions on recirculation of nutrients from society was not enough to cover all nitrogen and phosphorus removed from soils with harvest and losses. This shows the challenges of implementing organic farming on a large scale.

Ceased EU soybean feed imports without feed production encroaching on EU cropland currently used for other purposes relied on at least a 17% reduction in animal protein production.

This considerably reduced the demand for cropland in deforestation-prone regions in South America, where the majority of soybeans imported to the EU are grown. However, since most soybeans are processed to separate soybean oil (used for food and bioenergy) from soybean meal (used to feed animals), reduced use of soybean in animal feeding would also result in reduced production of soybean oil. The most likely candidate to replace this oil is palm oil. This would increase demand for cropland in Southeast Asia, with a potentially negative net effect on biodiversity. This could be avoided by increasing EU vegetable oil production.

Ruminant animals (cattle and sheep) were favoured over pigs and poultry when maximising food production.

This was because ruminant animals can make use of leys, permanent grasslands and other roughages, which accounted for a large share of feeds available in the different scenarios.

Swedish farms specialising in ruminant animal production had more varied landscapes, semi-natural grasslands and small-scale habitats and better crop sequences than nearby farms specialising in crop production.

In contrast, farms specialising in pigs or poultry were not associated with a higher score for any of the ecosystem services indicators analysed. This shows that farms with ruminants may contribute to more varied landscapes that promote ecosystem services, for example by providing habitats for pollinators and other beneficial insects. These farms also grow more ley, which can improve the soil and reduce the need for fertilisers and plant protection chemicals, but results showed that a large share of ley grown is not in rotation with other crops, which limits these positive effects. Results also showed that semi-natural grasslands attracted more visitors and were more frequently found within designated nature conservation or recreation areas compared with other agricultural land. This highlights the importance of these areas for nature recreation.

In conclusion, the results showed that cattle and sheep were favoured over pigs and poultry, both in terms of making use of leftover resources and in terms of managing agricultural landscapes for supply of ecosystem services. That said, beef consumption was still reduced when animals were only fed on leftovers, and not all farms with ruminants contributed equally to ecosystem services. For example, many ruminant animals contributed little to grazing Swedish semi-natural grasslands and these areas could potentially be managed with much fewer animals, which would reduce greenhouse gas emissions.

To take advantage of the positive contributions of livestock farming while limiting its negative impacts, the different actors in the food system need to facilitate the shift towards more plant-based diets, while providing incentives for livestock farmers to use leftover resources and manage agricultural landscapes for increased biodiversity and ecosystem services. The latter could include better incentives to graze semi-natural grasslands and keep small fields in production, as well as to introduce ley in rotations with food crops.

Populärvetenskaplig sammanfattning

Den offentliga debatten om djurhållningens roll i framtida hållbara livsmedelssystem är livlig och ofta polariserad. Det blir allt tydligare att konsumtionen av animaliska livsmedel måste minska i höginkomstländer för att begränsa miljöpåverkan och nå klimatmålen. Dessutom äter djuren för närvarande stora mängder spannmål och andra grödor som skulle kunna användas direkt som livsmedel - nästan hälften av all spannmål som odlas i Europeiska unionen (EU) används som djurfoder. Genom att istället använda dessa för direkt humankonsumtion skulle fler människor kunna få mat från samma landyta. Djurhållning kan dock bidra till ett hållbart livsmedelssystem på olika sätt. I debatten betonas ofta att djur spelar en nyckelroll när det gäller att utnyttja resurser som annars inte skulle vara tillgängliga för livsmedelsproduktion. Dessa "överblivna resurser" omfattar till exempel gräsmarker där det inte är möjligt att producera andra grödor eller olika former av biprodukter och avfall som inte är önskvärda som livsmedel. Dessutom kan djur bidra till att bevara den biologiska mångfalden och ekosystemtjänster, till exempel genom att beta naturbetesmarker eller genom att ge incitament för att inkludera vall i växtföljder, vilket kan förbättra jorden, binda kväve från luften samt begränsa skadedjur och ogräs. Detta är särskilt viktigt i ekologiskt jordbruk, men är också fördelaktigt i konventionell produktion. Syftet med denna avhandling var att ge ett kunskapsunderlag till debatten genom att kvantitativt undersöka djurens roll i att utnyttja överblivna resurser och bidra till ekosystemtjänster.

Två uppsättningar scenarier undersöktes i denna avhandling. Den första uppsättningen beskrev ett framtida livsmedelssystem i de nordiska länderna Danmark, Finland, Norge och Sverige där majoriteten av den konsumerade maten producerades ekologiskt inom Norden och där djurhållningen begränsades till att inte använda några resurser som kan användas för direkt livsmedelsproduktion. Dessa scenarier innebar en drastisk förändring jämfört med dagens livsmedelssystem. I den andra uppsättningen scenarier undersöktes därför ett potentiellt första steg i att minska användningen av livsmedelsdugliga grödor som foder. Här undersöktes en situation där EU slutade importera sojafoder.

Slutligen undersöktes djurens påverkan på jordbrukslandskapet och bidraget till ekosystemtjänster förutom livsmedelsproduktion. Här studerades sambandet mellan förekomsten av djur på en gård och olika indikatorer för ekosystemtjänster. I följande stycken lyfts några av de viktigaste resultaten av detta arbete fram och förklaras.

När djurhållningen begränsades till överblivna resurser kunde ekologiskt jordbruk i de nordiska länderna försörja en befolkning på upp till 37 miljoner människor (30 % fler än den beräknade befolkningen 2030).

I en sådan situation minskade köttkonsumtionen från sju till cirka en portion per vecka och den totala konsumtionen av animaliskt protein halverades. Användning av mineralgödselmedel tilläts inte i scenarierna, men resultaten visade att även vid optimistiska antaganden var återcirkulation av näringsämnen från samhället inte tillräckligt för att täcka behovet av kväve och fosfor. Detta visar på utmaningarna med att genomföra ekologiskt jordbruk i stor skala.

En stoppad import av sojafoder till EU samtidigt som ingen ytterligare åkermark inom EU används för foderproduktion förutsätter en minskad produktion av animaliskt protein med minst 17 %.

Detta minskade avsevärt efterfrågan på åkermark i Sydamerika, där majoriteten av de sojabönor som importeras till EU odlas och där denna odling orsakar avskogning. Eftersom de flesta sojabönor processas för att separera sojaolja (som används till livsmedel och bioenergi) från sojamjöl (som används som djurfoder), skulle en minskad användning av sojafoder också leda till minskad tillgång på sojaolja. Den mest sannolika kandidaten för att ersätta denna olja är palmolja. Detta skulle öka efterfrågan på åkermark i Sydostasien, med en potentiellt negativ nettoeffekt på den biologiska mångfalden. Genom en ökad produktion av vegetabilisk olja inom EU skulle detta kunna undvikas.

I scenarierna föredrogs idisslare (nötkreatur och får) framför grisar och fjäderfä för att producera så mycket mat som möjligt.

Detta beror på att idisslare kan utnyttja vall, gräsmarker och annat grovfoder, vilket stod för en stor del av det tillgängliga fodret i de olika scenarierna.

Svenska gårdar som specialiserat sig på mjölk-, nöt- och fårproduktion hade mer varierade landskap, naturbetesmarker och småbiotoper samt bättre växtföljder än närliggande gårdar som specialiserat sig på växtodling.

Gårdar som specialiserat sig på grisar eller fjäderfä var däremot inte förknippade med högre värden på ekosystemtjänstindikatorerna. Detta visar att gårdar med idisslare kan bidra till mer varierade landskap som främjar ekosystemtjänster, till exempel genom att tillhandahålla livsmiljöer för pollinatörer och andra nyttoinsekter. Dessa gårdar odlar också mer vall som kan förbättra jorden och minska behovet av gödnings- och växtskyddsmedel. Resultaten visade dock att vallarna sällan var i en växtföljd med andra grödor, vilket begränsar dessa positiva effekter. Naturbetesmarker lockade fler besökare och låg i större utsträckning inom utsedda naturskydds- eller friluftsområden än annan jordbruksmark. Detta understryker betydelsen av dessa marker för rekreation och friluftsliv.

Sammanfattningsvis visade resultaten att nötkreatur och får föll bättre ut än svin och fjäderfä, både när det gäller att utnyttja överblivna resurser och när det gäller att förvalta jordbrukslandskapet för att tillhandahålla ekosystemtjänster. Men, nötköttskonsumtionen minskade fortfarande när djuren endast utfodrades med överblivna resurser och alla gårdar med idisslare bidrog inte lika mycket till ekosystemtjänsterna. Till exempel bidrog många idisslare i begränsad utsträckning till betandet av svenska naturbetesmarker och dessa områden skulle potentiellt kunna betas med mycket färre djur, vilket skulle minska utsläppen av växthusgaser.

För att dra nytta av djurhållningens positiva bidrag och samtidigt begränsa dess negativa effekter måste de olika aktörerna i livsmedelssystemet underlätta övergången till mer växtbaserade kostvanor, samtidigt som djuruppfödare ges incitament att använda överblivna resurser och förvalta jordbrukslandskap för ökad biologisk mångfald och ekosystemtjänster. Det sistnämnda skulle kunna inbegripa bättre incitament att beta naturbetesmarker och behålla små åkrar i produktion, samt att introducera mer livsmedelsgrödor tillsammans med vallen i växtföljder.

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RESEARCH ARTICLE

Designing a future food vision for the Nordics through a participatory modeling approach

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Abstract
The development of future food systems will depend on normative decisions taken at different levels by policymakers and stakeholders. Scenario modeling is an adequate tool for assessing the implications of such decisions, but for an enlightened debate, it is important to make explicit and transparent how such value-based decisions affect modeling results. In a participatory approach working with five NGOs, we developed a future food vision for the Nordic countries (Denmark, Finland, Norway and Sweden) through an iterative process of defining the scenario, modeling, and revising the scenario, until a final future food vision was reached. The impacts on food production, land use, and greenhouse gas emissions, and the resulting diets in the food vision, were modeled using a mass flow model of the food system. The food vision formulated was an organic farming system where food is produced locally and livestock production is limited to "leftover streams," i.e., by-products from food production and forage from pastures and perennial grass/clover mixtures, thus limiting food-feed competition. Consumption of meat, especially non-ruminant meat, was substantially reduced compared with current consumption in the Nordic countries (− 81%). An estimated population of 37 million people could be supplied with the scenario diet, which uses 0.21 ha of arable land and causes greenhouse gas emissions of 0.48 tCO_2e per diet and year. The novelty of this paper includes advancing modeling of sustainable food systems by using an iterative process for designing future food visions based on stakeholder values, which enables results from multidisciplinary modeling (including agronomy, environmental system analysis, animal and human nutrition) to be fed back into the decision-making process, providing an empirical basis for normative decisions and a science-based future vision of sustainable food systems.

Keywords Food system · Local · Organic · Livestock · Leftovers · Food-feed competition · Default livestock · Land use · Greenhouse gas emissions · Agriculture

1 Introduction

Agriculture faces a massive dual challenge in feeding a growing and increasingly affluent global population, while at the same time reducing its negative environmental impacts. Food systems affect the environment through agricultural land expansion, where agriculture extends into other biomes with negative impacts on biodiversity, soils and stored carbon, and through intensification, with increased water withdrawal, perturbation of nutrient cycles, and increased energy use (Foley et al. 2011). Up to 29% of global anthropogenic greenhouse gas (GHG) emissions can be attributed to food systems (Vermeulen et al. 2012), where livestock products, especially red meat, are GHG-intensive and responsible for a large part of the GHG impact of diets (Hallström et al. 2015). While the goal for future food systems is clear, i.e., to produce enough nutritious food accessible to everyone while reducing negative environmental impacts, the paths suggested to reach this goal are numerous and sometimes opposing.

Some experts call for further improvements in efficiency, to produce more from existing land through increased and more efficient use of inorganic fertilizers, pesticides, and other amendments and modern technologies, in order to increase

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the per-hectare yields. This strategy is often called "sustainable intensification" (e.g., Burney et al. 2010). However, as the historical focus on higher productivity has come at a cost to the environment (Foley et al. 2011), and has not been able to end global food insecurity, others see high-input modern farming itself as the problem. They call instead for reduced external inputs, improved nutrient cycling, and a greater dependence on local resources, as in organic farming (Reganold and Wachter 2016). This approach has been criticized in turn for not providing an answer as to how the world's population can be fed without causing further expansion of agricultural land, as yield per area in low-input organic farming is usually lower (Connor 2008).

It is also becoming increasingly clear that a dietary change away from diets high in animal products towards more plant-based foods and reductions in food waste are needed to reach, e.g., climate targets (Bajželj et al. 2014). In addition, reallocation of crops from animal feed to direct human food production could substantially increase food supply worldwide, as one third of global cereal production is currently used to feed animals (Mottet et al. 2017).

A range of different approaches will arguably be needed to transform the current food system into one that sustainably produces enough food for everyone. However, the future is uncertain, food systems are highly complex, and optimal solutions are highly context-specific. The composition of future human diets and the environmental and social impacts they cause will depend on the type of approach invested in, which in turn will depend on general visions of "good," faith in technology, and beliefs about what can be changed (Garnett 2014; Smith 2013). Modeling of future food systems can increase knowledge of possible implications of different choices in the evaluation of more sustainable food systems. The process of designing such futures to model is inevitably associated with unavoidable normative decisions at different levels that have to be taken in a democratic and transparent process by key stakeholders rather than researchers. It is crucial that such stakeholder decisions are taken in an unprejudiced way, based on the best empirical evidence available (Muller et al. 2017). Participatory research, where knowledge is co-created through collaboration between researchers and non-academic stakeholders, markets, and government institutions, has been proposed as a fruitful endeavor in research on complex sustainability transition problems (Mauser et al. 2013; Volkery et al. 2008). Direct involvement of stakeholders and inclusion of goals, norms, and visions will be needed to create deeper legitimacy, ownership, and accountability regarding the problem and proposed solutions.

In the present study, we worked with a group of non-government organizations (NGOs) in a participatory scenario development process to jointly define a future food vision for the Nordic countries (Denmark, Finland, Norway, and Sweden), based on the values and views of these NGOs. The aim of this paper is to describe this process and the modeled results in terms of food production (including nutritional aspects), land use (i.e., how many people can be provided with a complete diet from the Nordic land base), and the climate impact of this future food vision. In the following sections of this paper, we illustrate and discuss how normative decisions and assumptions made during scenario development influenced the results of the modeling.

2 Materials and method

2.1 The Nordic food system

The Nordic countries are part of a highly globalized food system with resource-intense consumption patterns, e.g., meat consumption in the Nordic countries is around double the global average. Due to the large Danish pork industry, the region is also a net exporter of meat. Within the region, Denmark is the only country with net export of agricultural commodities, while the other countries are net food importers (FAO 2017). A relatively small proportion of the total land area (3–8%) is used for agricultural production in all countries except Denmark (~ 50%). Specialist dairy farming (Fig. 1) is the most economically important farm enterprise in Finland, Norway, and Sweden, while specialist pig production is the most prominent enterprise in economic terms in Denmark. Due to the harsh weather and topography in Norway, specialist sheep farms are also common, utilizing remote pastures in hilly areas. All the Nordic countries have experienced an increase in average farm size in recent decades due to smallholders ceasing operations and merging into larger farms (Eurostat 2016). However, smallholders are still relatively important in Norway. At the national level in all countries, only 2–3% of the total workforce is employed in agriculture. The emissions of methane and nitrous oxide from agriculture constitute a considerable part of total national greenhouse gas emissions; 8, 9, 13, and 19% in Norway, Finland, Sweden, and Denmark, respectively. Ammonia emissions, mainly from livestock manure, account for approximately 90% of total ammonia emissions in the Nordic countries (Antman et al. 2015). The Baltic Sea, which Sweden, Finland, and Denmark border, is heavily affected by eutrophication due to nutrient pollutants lost from agriculture.

2.2 Stakeholder engagement process

Based on the methodologies presented by Volkery et al. (2008) and Mauser et al. (2013), an iterative stakeholder integration process was employed to design and model the future food vision for the Nordic countries. The process followed the three principal steps suggested by Mauser et al. (2013) to define normative decisions describing the food vision and

Fig. 1 Dairy calves grazing in the central Swedish lowlands with extensive cultivation of grass leys in the background which is typical for many parts of the Nordic region. Photo: Jannie Hagman, SLU

translate these decisions into quantitative model inputs. The NGOs provided the creative input when defining normative decisions, while the researchers were responsible for translating the normative decisions into quantitative model inputs and running the model. The process was iterated until a compelling and reasonable set of decisions and model outputs was obtained.

The group of NGOs participating in the study was a rather homogeneous group consisting of five environmental and small-scale farmers' organizations: *Miljøbevægelsen NOAH* (Denmark), *Frie Bønder - Levende Land* (Denmark), *Uusimaa Region of Finnish Association for Nature Conservation* (Finland), *Norsk Bonde-og Småbrukarlag* (Norway), and *The Air Pollution and Climate Secretariat* (Sweden) (hereafter "the NGOs"). They had previously worked together on food system sustainability (see Antman et al. 2015) and had already started to define common interpretations of problems and potential solutions in the area. With this said, each NGO entered into the process with different agendas and local knowledge.

The first step in the process involved initial communications between the researchers and the NGOs in which the overall aim, framing, and initial pre-conditions for the work were decided (see Sect. 2.3). This was followed by collaborative data acquisition and method development (see Sect. 2.4). Collection of data was facilitated by the NGOs' networks in their home countries. In late October 2016, a first workshop involving the researchers and representatives of the NGOs was held in Oslo, where the researchers presented the methodological approach and preliminary model results. Questions regarding what a future sustainable food system should comprise were discussed and key normative decisions were determined (see Sect. 2.3). During this workshop, each NGO provided insights into the political discourse in their respective home country, information which was used to frame the work in a way that was relevant for each of the participating NGOs. Furthermore, the NGOs provided local knowledge on agricultural practices and particularities in their respective home country.

The first workshop was followed by continued method development and modeling work where the decisions made were fed back into the model. This resulted in a draft project report containing the methodology and results.

In early 2017, the NGOs organized four workshops, one in each of the case countries, and invited participants from a broad spectrum of stakeholders, including representatives from farmers' unions, producers, retailers, government agencies, and environmental organizations. The participants had the opportunity to read the draft project report beforehand. During the workshops, they were given a presentation on the main results, which they were asked to discuss and respond to. After the workshops, the researchers and NGOs reviewed the outcomes and lessons learnt, which were fed back into the process of framing the work. Some methodological issues identified during the workshops were also discussed and resolved.

A final step in the participatory process is co-dissemination of results, where findings are openly discussed among participants and other stakeholder groups, and results are published through channels relevant for all participating parties (Mauser et al. 2013). This was done through a co-authored report published by the Nordic Council of Ministers in late 2017 (Karlsson et al. 2017), and the findings were also discussed at the COP 23 meeting in Bonn in November 2017. At the time of writing, a series of debate articles in the different countries has been authored by the NGOs and submitted to relevant newspapers and a final workshop is planned.

2.3 Normative choices in developing the future food vision

This section provides some details on the background to the normative decisions made and the discussions leading to these. The aim is to give an understanding of the ideological views and opinions behind the decisions which shaped the results and conclusions of this modeling study. Key normative decisions and their implications on the modeled scenario are summarized in Fig. 2 and further details can be found in Karlsson et al. (2017).

Early in the process, it was decided that the food vision should depict a future where food is produced mainly through agriculture and not in highly technical landless systems (Muller et al. 2017). Furthermore, one key concept used by the NGOs was that of agroecology (Wezel et al. 2009). One important aspect of agroecology as interpreted by the NGOs

Fig. 2 The main normative decisions resulting from an iterative stakeholder process and how these decisions were implemented in the modeling. The normative decisions are grouped according to which area of the food system they concern, although many span multiple food system areas

was to attempt to re-establish the link between available local resources, food production, and diets consumed. From this, it emerged that food systems need to be re-localized and the reliance on food imports reduced. However, limited imports of tropical fruits, tea, coffee, and chocolate were included in the scenario, as these cannot be produced in the region. Livestock, especially grazing livestock, were considered a vital component in re-localizing the food system, through their ability to utilize local pasture resources, and also by-products from food processing, to produce food. Livestock production should hence not be reliant upon imported feed or compete with local plant-based food production, but instead rely on "leftover streams," i.e., biomass not consumed by humans, a concept referred to as "default livestock" (Van Zanten et al. 2018). The leftover streams available as livestock feed in this study were

1. Semi-natural pastures and Norwegian outfield areas (i.e., forest and mountainous pastures, not counted as agricultural land), where grazing can promote biodiversity and annual cropping is unfeasible
2. Perennial grass or grass/clover mixtures (referred to as ley) grown in crop rotations to facilitate biological nitrogen fixation and control of weeds
3. By-products from food processing unfit or unwanted for human consumption

In Norway, pasture resources outside the areas defined as agricultural land (outfield areas) were considered a resource base for grazing livestock. Outfield areas are currently an important part of Norway's animal husbandry and were considered by the NGOs to be a vital domestic resource that should be utilized for food production.

Together, these leftover streams represented the base upon which livestock production was performed in the future food vision. This limited meat, milk, and egg production to regionally available resources that were not in competition with plant-based food production. However, to enable a large utilization rate of pasture resources and by-products, this normative choice necessitated animal production systems with low productivity compared with current levels.

Another aspect of agroecology suggested for inclusion in the future vision by the NGOs was use of organic farming practices, such as exclusion of synthetic fertilizers and pesticides. This decision led to modeled crop rotations with a large share of grass-legume leys to supply biological nitrogen fixation and to limit pests and weeds, limitations on some crops prone to disease if grown too frequently and also reduced per hectare crop yield (for most crops) compared with current conventional farming practices.

To promote biodiversity in agricultural landscapes, the NGOs decided to set aside 15% of arable land in Denmark for nature conservation. In the other countries, agriculture is a minor land user, which is why this was only applied to the Danish case. The NGOs also decided that semi-natural pastures should be grazed by livestock to prevent them from reverting to natural vegetation, an outcome which would lead to loss of many endangered species that are dependent upon semi-natural pastures.

It was decided that the diets should be based on the type of food currently consumed in the region and seek to fulfill Nordic nutrition recommendations (Nordic Council of Ministers 2014). Therefore, a sample diet produced by the Swedish National Food Agency (Enghardt-Barbieri and Lindvall 2003) was used as a "baseline" diet from which the scenario diets were developed. This baseline diet was based on current Swedish consumption patterns but adjusted to conform to nutrient recommendations. Reduced consumption of animal products compared with the baseline diet was replaced with plant-based counterparts (i.e., cereals, grain legumes, and vegetable oil) to provide the same amount of energy and to meet fat and protein requirements according to the Nordic nutrition recommendations. Dietary carbohydrate content and intake of 20 vitamins and minerals were also assessed and compared to recommendations.

The current levels of food waste were considered unsustainable, and it was agreed that future scenarios for food production should include reduced food waste. Avoidable food waste at the retail and consumer stage of the food chain was therefore assumed to be halved compared with current levels of waste, which is also in line with the United Nations Sustainable Development Goal 12, Target 12.3.

Regarding the energy system, it was decided that the vision should depict fossil-free agriculture. This was enabled through the use of non-food biomass (i.e., wastes, manure, straw, and grass legume leys) for bioenergy production. There was some skepticism among the NGOs about the use of agricultural biomass for bioenergy production and some had previously campaigned actively against the use of arable land for energy production, due to its competition with food production. However, they agreed that limited bioenergy production to cater for energy needs within the agricultural sector was acceptable.

In light of a changing climate and uncertainties in future agricultural productivity in many parts of the world, it was agreed that, instead of restricting food production to the need of the local population, the focus should be on the maximum food production potential based on local resources, in order to feed as many as possible.

2.4 Modeling the future food vision

An adapted and extended version of the bottom-up agricultural mass flow model from Röös et al. (2016) was used to model the impacts of the future food vision on (1) food production including nutrient content in resulting diets, (2) land use, and (3) GHG emissions. Modeling was performed separately for each country. The model tracks mass flows between four main subsystems (crop production, animal production, bioenergy production, and food processing and consumption) and includes 16 crop groups (e.g., cereals, rapeseed, cabbage, potatoes, ley, etc.), 5 animal species (dairy cattle, sheep, pigs, poultry, and aquaculture), and 32 different food items (e.g., cereals, vegetable oil, cabbage, cheese, fish, etc.). The nutrient content of the resulting diets was analyzed with the DietistNet software, using the Swedish National Food Agency's food database. The global warming potential (GWP) was calculated for the GHG methane, nitrous oxide, and carbon dioxide over a 100-year timeframe, according to the 5th IPCC assessment report (IPCC 2013).

Emissions were assessed from cradle to farm gate, thus excluding emissions generated in post-harvest transport, processing, and storage. Changes in soil carbon stocks in arable soil were modeled using the Introductory Carbon Balance Model (ICBM, Andrén et al. 2004) for the Swedish case only due to data limitations and presented separately. Average carbon sequestration (or emission) rates were calculated over a 100-year timeframe. Agricultural energy expenditure was accounted for in the model, and biomass was allocated for bioenergy to provide for farm energy needs. Farmyard manure, food, and slaughterhouse wastes, together with straw and ley, were used as feedstocks, and the digestate was used as fertilizer. For a more detailed description of the model and impact assessment, please see Karlsson et al. (2017).

The area needed to produce all plant-based food in the baseline diet and the bioenergy crops, feed crops, and additional food crops needed to replace reduced consumption of animal products was calculated using national statistics on crop yields. Since data were not available for organic production of all crop groups in all countries, conventional yields were used and the yield gap between conventional and organic farming was accounted for using literature values from de Ponti et al. (2012). Land use for imported food was calculated using global average yield levels according to FAOSTAT.

All crops (except greenhouse horticulture and apple orchards) were grown in crop rotations containing at least one-third grass-legume leys (i.e., ley grown for 2 years in a 6-year rotation), which is recommended for good nitrogen supply and for preventing agricultural pest problems (i.e., weeds, arthropods, and diseases). Ley yield data were taken from national statistics and adjusted for statistical bias using results from Swedish ley field experiments. Limitations in terms of harsh winters and short growing seasons in the northern parts of the Nordic countries and how often specific crops can be incorporated in the crop rotation to avoid build-up of pests were accounted for by limiting cultivation of rapeseed and grain legumes to the southern parts of the countries and restricting their cultivation frequency.

Food chain by-products unfit or unwanted for human consumption were used as animal feed. These were rapeseed cake from vegetable oil production, low-grade roots and potatoes, residue cereal bran, bakery wastes, spent grains from beer production, fiber and molasses from sugar production, and fishmeal from gutting and cleaning.

Livestock herd structures and allocation of feed resources (by-products, grass feed, and feed grains grown on arable land) were identified using a non-linear optimization algorithm described in Karlsson et al. (2017). The model included five livestock systems: (1) low-yielding dairy systems relying on pasture resources to a large extent, (2) lamb production where lambs are reared on pastures during summer and slaughtered in the autumn, (3) organic pork production with access to pastures on arable land, (4) dual-purpose poultry producing eggs and also meat by rearing cockerels, and (5) land-based fish farming using Nile tilapia that can be reared on plant-based feed. For details, see Karlsson et al. (2017).

3 Results and discussion

3.1 Contribution of the Nordic countries to food security

The future food vision formulated has the potential to provide complete diets for an estimated 37.0 million people. The current population in the Nordic countries is 26.5 million and is expected to reach 28.4 million by 2030 (United Nations 2017). However, the aggregated Nordic case masks large differences between the individual countries, e.g., in the Norwegian case, the future vision could only support the dietary requirements of some 51% of its projected 2030 population; in the Danish case, it could provide diets for a much larger population (262% of its projected 2030 population); and in the case of Sweden and Finland, it could provide 102 and 116%, respectively, of the projected 2030 population with the food they require. These differences arose directly from differences in available arable land and average crop yields in the four countries. Thus, our results indicate that a local food system at the national level is not feasible for all Nordic countries. However, via exchange of food between and within the different countries in the region, this would be possible.

3.2 Scenario diets and nutrition

The weekly diets (Fig. 3) were composed of 110–340 g of meat (including poultry), 70–190 g of eggs, 90–200 g of fish, 3100–3400 g of dairy products, 2000–2200 g of cereals, 120–190 g of legumes, 260–390 g of vegetable oil, 1400 g of potatoes, 2400 g domestically grown vegetables, roots and fruits (partly in the form of beverages), and 680 g of imported fruits, tea, and coffee. Currently, a large amount of cereals and legumes grown in the Nordic regions is fed to animals, e.g., approximately 60% of Swedish grain is used as animal feed. The decision to limit livestock production to available leftover

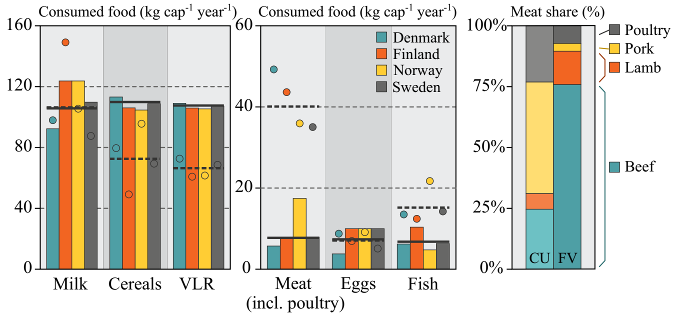

Fig. 3 (Left and center) Yearly per-capita consumption of milk products, cereals, vegetables, legumes and roots (VLR), meat (incl. poultry), eggs, and fish in the future food vision diets (bars) and in current diets (circles). Solid lines represent the aggregated Nordic case for the scenario and dotted lines current average consumption in the Nordic countries. (Right) Share of beef, lamb, pork and poultry meat in the current case (CU) and future vision (FV) of total meat consumption

streams had dramatic impacts on meat supply. Compared with current levels, meat consumption decreased on average 81%, to weekly per-capita consumption of 150 g. The decrease was largest for non-ruminant meat (− 97%), while for ruminant meat, the reduction was "only" 44%. The scenario diets ended up well below the 500 g of red meat a week recommended by the World Cancer Research Fund (WCRF 2007). The high share of ruminant meat compared with non-ruminant meat remaining in the diets was a consequence of both the "default livestock" approach and the choice to base cropping on organic practices. Ruminants are better utilizers of leftover streams, especially ley, which was cultivated on large areas in the future food vision (Fig. 4) due to its importance in organic cropping systems, thus feeding more ruminant animals.

To replace dietary energy, protein, and fat following reduced consumption of animal products, additional cereals, grain legumes, and vegetable oil had to be cultivated and incorporated into diets. These replacement foods contained on average less protein and fat per unit energy, which resulted in carbohydrates constituting 61–63% of dietary energy (E%) in the scenario diets, exceeding the Nordic nutrition recommendation of 45–60 E% but staying within the range recommended by the WHO of 55–75 E% (Amine et al. 2003). In our calculations, we did not include any processing of leguminous food prior to consumption, but processing could be performed to increase the protein and fat-to-energy ratio, addressing the high carbohydrate content in the scenario diets. The protein content (12–13 E%) and total fat content (25–26 E%) were both within the Nordic (10–20 E% protein and 25–40 E% fat) and WHO recommended range (10–15 E% protein and 15–30 E% fat). The scenario diets complied with recommendations on saturated fatty acids and dietary fiber, while current diets exceed the recommendation for saturated fat and provide insufficient amounts of fiber.

The scenario diets did not meet the Nordic nutrition recommendations for 6 of 20 micronutrients assessed. These were vitamins A and D, riboflavin, iodine, iron, and selenium. Of these, vitamin D, riboflavin, iron, and selenium (except in Finland) are also low in current diets. For folate, the scenario diets met the recommendations, while current diets are below recommendations. For both iodine and selenium (only in Finland), the recommendations are met in the current diets mainly through fortification, which is also a viable option for the food vision diets. For other nutrients such as vitamin A and iron, selection of foods within broader groups is important. For vitamin A, increased consumption of carrots and

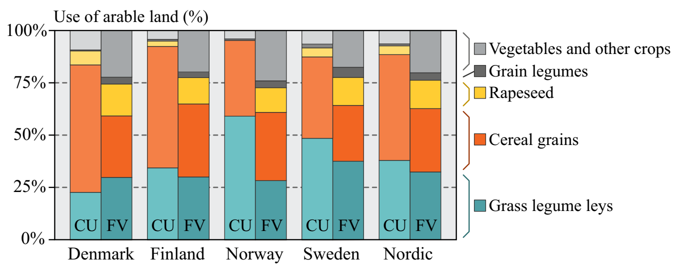

Fig. 4 Share of arable land used for (from bottom to top): grass legume leys, cereal grains, rapeseed, grain legumes, and vegetables and other crops, including horticultural crops, roots, and apples. The left bars show current (CU) land use according to national statistics and the right bars show land use in the future food vision (FV)

other vegetables rich in carotene is an option, while for iron increasing, the fraction of whole grain cereals could improve nutrition. Vitamin D is mainly found in oily fish and (due to fortification) in milk and some plant-based milk alternatives, but intake is still inadequate for a large part of the population (Nordic Council of Ministers 2014). In summary, the scenario diets were associated both with nutritional benefits and challenges that would need to be handled by, e.g., choice of products within broader food groups and fortification strategies for some critical nutrients.

3.3 Land use and climate impact

For the Nordic countries on aggregate, a total of 0.21 ha of agricultural land was needed to produce a per-capita diet and an additional 0.01 ha was needed outside the Nordic countries to produce the imported foods. Semi-natural pastures made up 11% of the total agricultural area, and the rest, 0.19 ha, was arable land. The global land availability per capita in 2030 based on currently available agricultural land would be 0.57 ha of agricultural land, of which 0.19 ha would be arable (FAO 2017). Thus, if global arable land were to be shared equally, the scenario diets would be just on this threshold, while the total use of agricultural land would be well below the global per-capita availability.

The choice in this study to rely on local food systems and produce most foods within the region meant that agriculture in the Nordic countries had to diversify substantially, which is also consistent with previous findings on regional food self-sufficiency (Pradhan et al. 2014). Compared with the current use of arable land in the Nordic countries, cereal cultivation had to be drastically reduced (− 46%) and cultivation of grain legumes (+ 242%), oilseed crops (+ 188%), fruit and vegetables (+ 258%), and potatoes (+ 134%) had to increase substantially.

A total of 34% of arable land in the future vision was used for livestock feed production and grazing, while 7% was used for bioenergy production and the rest to produce food for direct human consumption, of which 6% was used to grow supplementary plant-based foods (i.e., legume grains, cereals, and vegetable oil) to compensate for reduced consumption of animal products (Fig. 4).

In total, 60 PJ of biogas was produced to provide electricity and heating for production buildings and propellant for agricultural machinery. Thirty-five percent was supplied from harvested leys and the rest from manure and slaughter house and food waste. Apart from the biogas, straw was burned to produce an additional 9.3 PJ of heat and 2.6 PJ diesel was used by the fishing fleet. The climate impact from field to farm gate was estimated to be 0.48 tCO_2e per diet and year, comprising mainly methane emissions from enteric fermentation and nitrous oxide emissions from soils (Fig. 5). To our knowledge, no previous study has assessed the climate impact of diets currently consumed in the Nordic region, but two studies have

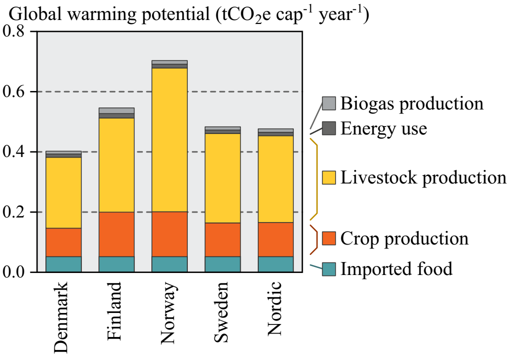

Fig. 5 Estimated climate impact per diet and year of the future food vision for the different case countries and the Nordic region. Emissions are divided between (from bottom to top): Emissions outside the region, related to imported food; emissions directly from crop production; emissions related to livestock production and manure management; emissions from combustion of fossil and biofuels; and emissions from biogas production and storage of biogas digestate

estimated that the Swedish and Finnish diet cause emissions of 1.8 and 2.8 tCO_2e, respectively, of which around 70% is attributable to agricultural activities (Röös et al. 2015; Virtanen et al. 2011). The climate impact can also be compared to emission pathways with a "likely" chance of keeping global temperatures below + 1.5 °C compared with pre-industrial levels, which require global anthropogenic GHG emissions to drop to around 27 $GtCO_2e$ $year^{-1}$ by 2030 (3.2 tCO_2e cap^{-1} $year^{-1}$), 6 GtCO2e $yr.^{-1}$ by 2050 (0.6 tCO_2e cap^{-1} $yr.^{-1}$) and reach zero or net negative emissions in the long term (Sanderson et al. 2016). The GHG emissions from the future Nordic diets corresponded to 11–15% of the 2030 per-capita emissions space and 58–78% of the 2050 emissions space. Considering that the food system currently accounts for some 29% of global emissions (Vermeulen et al. 2012), the scenarios can be considered in line with the near-term pathway (i.e., up until 2030), without increasing the food system's share of the emission space. However, later on in this century, greater reductions would be necessary, or other sectors would need to take more responsibility for greenhouse gas mitigation, allowing food systems to use a larger share of the available emission space in the future.

Changes in soil carbon stocks on arable land were modeled for the Swedish case and resulted in net emissions of 0.06 tCO_2e per diet and year compared with a situation in which current land use continues. The modeled soil carbon losses followed mainly from lower yields and reductions in ley cultivation. Adoption of organic farming practices has previously been associated with increased soil carbon stocks (Gattinger et al. 2012) while our results suggest the opposite. One explanation for this could be that it is already common to include grass and legume leys in crop rotations in Swedish agriculture, and thus the organic crop rotations assumed in this study did not involve increased cultivation of leys, while modeled yields were lower, resulting in a reduced carbon input compared with the current situation.

3.4 Key normative decisions and their impacts on results

The three most important normative choices that determined the outcome in terms of the number of people that could be fed, the food in diets, the land use, and the climate impact were (i) basing production on organic farming and agro-ecological principles, (ii) limiting livestock production to feeds based on leftover streams, and (iii) relying on local food systems. Producing all food in an organic system would most likely lead to lower per-hectare crop yields compared with conventional farming, but this was compensated for by reduced cultivation of feed grains in the future food vision, enabling a large food output. To account for reduced yields, we used data on observed yield gaps for different crop groups in field trials comparing organic and conventional practices. Observed organic yields were on average 20% (de Ponti et al. 2012) lower than conventional yields at field level. However, it is not certain that these yields would be achieved at the food system level, which would affect both the total food output and food composition in the future food vision.

In the future food vision, animals were an integral part of the farming system, utilizing the grass from leys and biomass from outfield areas to produce highly valued food (milk and meat) but inevitably also emitting GHGs. Another food future could have been to promote a completely plant-based diet. Vegan diets have been shown to have the lowest climate impact (Hallström et al. 2015), which would have decreased GHG emissions even further, but possibly slightly increased land use (Van Zanten et al. 2018). However, due to the agro-ecological approach chosen by the stakeholders, a totally plant-based vision was not seen as a viable alternative. Yet another approach could have been to model a more moderate reduction in meat consumption, referring to what might be considered a more "realistic" goal in terms of dietary change (e.g., a reduction in meat consumption of 50% following an international contraction and convergence strategy, as suggested by McMichael et al. (2007)) and a strong reduction in ruminants (to cut methane emissions) in favor of more efficient fish and poultry production. However, while such an approach would have been in line with the aim of the NGOs to reduce GHG emissions drastically, fish and poultry would not have been able to utilize biomass from the leys.

Another important decision that affected the results was feeding as many people as possible using agricultural land in the Nordic countries. An alternative could have been to divide the amount of produce by the projected Nordic population in 2030, which would have yielded diets with higher amounts of animal products, higher land use, and higher GHG emissions per capita. The decision to share the Nordic agricultural production over more people was taken by the NGOs based on the moral responsibility of the Nordic region to supply as much food as possible, as this region is one of few that will potentially experience more favorable growing conditions due to climate change.

The results also depend on the assumed decrease in food waste of 50% from current levels. If such a decrease could not be achieved, the number of people that could be fed in the future vision would decrease. It was decided to use ley mainly for animal feed and only to a limited extent for bioenergy production. Allocating more ley to bioenergy production would have led to fewer ruminants and diets with lower GHG emissions and also enable substitution of fossil fuels in other sectors, but would also lead to diets with even less animal products and with higher land requirements, thus feeding fewer from Nordic agriculture. Furthermore, bio-refinement, i.e., extracting macro- or micronutrients to produce human food directly, may become a viable option for many of the resources considered as leftovers here, thus bypassing the need for livestock. However, it was decided here that the future food vision diet should be based on foods currently consumed in the region.

4 Conclusions

This is the first paper to describe a process in which researchers in agronomy, animal science, nutrition, and systems analysis and stakeholders with a desire to promote more sustainable food consumption and production in the Nordic countries worked together in an iterative manner to sketch out, model, and evaluate a future food vision for Sweden, Norway, Denmark, and Finland. This future food vision, based on organic local food production and designed to avoid food-feed competition, involves a drastic reduction in meat consumption, greatly diversified agriculture, land use that can be considered "fair" from a global perspective, and a climate impact in line with emission pathways compatible with the Paris agreement. The study provides important insights into both the process of designing food futures with stakeholder engagement and the outcomes in terms of food production and environmental impacts of unavoidable normative decisions taken when designing the food vision. Implementation of such a vision requires strong support and collaboration on several societal levels, including changes in agricultural practices, food processing, policies, and consumer behavior, aspects that were not investigated here but are important areas for future research and investigation.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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Resource-efficient use of land and animals—Environmental impacts of food systems based on organic cropping and avoided food-feed competition

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ABSTRACT

Current food systems are resource-inefficient, as farm animals consume large quantities of human-edible crops and large amounts of external fossil fuel-based inputs are used for energy and fertilisers. In this study, we assessed the production capacity and environmental performance of an alternative theoretical regional food system based on organic production, avoided food-feed competition and agriculture that is self-sufficient in bioenergy. Livestock in the system are reared solely on feeds that do not compete with food production, i.e. grass from permanent pastures, temporary grass-clover leys and food industry by-products. We modelled the effect of this food system on food production, land use, environmental impacts and nutrient flows, using the Nordic region as a case. As crop rotations under organic farming need leguminous forage crops to supply nitrogen and control weeds, substantial amounts of grass biomass suitable for feeding ruminants are produced in the system. Modelling showed that such a food system could feed 109% of the projected Nordic population in 2030 in a scenario where ruminant production is limited by the availability of semi-natural grasslands, and 130% in a scenario in which all grass biomass produced in organic crop rotations is used as animal feed. However, even when all grass biomass is used for animal feed, the associated reduction in meat production led to diets with 81% less meat compared to current consumption in the Nordic region. Using all ley from the organic crop rotations as livestock feed would result in greater total food output and reduced land use per person, but also a larger climate impact per person due to more livestock production. There is thus a trade-off between optimising the food system for efficient land use or for 'climate efficiency'. Assessments of nutrient supply showed nitrogen and phosphorus deficits in both scenarios, but particularly in the scenario in which all grass biomass is used for animal feed, due to nutrient losses in animal production. Increased recycling from society and other innovative sources of essential soil nutrients are needed to counterbalance removal and losses. Through utilising leftover streams and hence minimising food-feed competition and reducing livestock production, we show that organic agriculture can maintain high food output, sufficient to feed the future Nordic population and more, despite lower yields.

1. Introduction

Future food systems will need to cope with a growing and increasingly affluent global population, while at the same time preventing expansion of agriculture into pristine ecosystems and drastically reducing other negative impacts on the environment. Past growth in agricultural output has largely been met by increased yields, but in recent years yield improvements have slowed (Foley et al., 2011), increasing the risk of further expansion of agriculture in response to higher demand for agricultural produce. Expansion of agricultural land is one of the most important drivers of terrestrial biodiversity loss (Newbold et al., 2015) and agriculture is the main driver of anthropogenic disruption of the nitrogen cycle, with effects on eutrophication and the climate (Fowler et al., 2013).

Food systems contribute some 19–29% of global anthropogenic greenhouse gas (GHG) emissions (Vermeulen et al., 2012), while livestock alone are estimated to account for 14.5% (Gerber et al., 2013). Along with reduction in food waste and production side improvements, many see a need for large-scale dietary changes towards more plant-based diets (Bajželj et al., 2014; Röös et al., 2017). Around half the world's agricultural area and 40% of all arable land is used for livestock feed production and grazing (Mottet et al., 2017). Due to metabolic losses when livestock convert feed into food, re-allocation of arable land from feed production to direct human food production would

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considerably increase global food availability (Foley et al., 2011; West et al., 2014). Different livestock systems utilise feed resources differently, in terms of both quality and quantity. Compared with non-ruminant livestock systems, ruminant systems deliver less human-edible protein per unit of feed but a large part of that feed is from grass resources not edible to humans. Thus ruminant systems generally deliver more protein per unit feed that is edible to humans (Mottet et al., 2017).

In the current food system, production of animal feed competes with food production, with negative implications for total food supply. Therefore a growing body of literature has explored the concept of limiting livestock production to resources that humans cannot or will not eat, so called ‘leftovers’ or ‘leftover streams’ (Van Zanten et al., 2018 provides a review). In previous studies, leftover streams have included land use based leftovers (i.e. grass biomass from permanent grasslands where annual cropping is unfeasible), as well as food wastes and non-determining co-products or by-products from food processing (i.e. products not driving an increase in production volume), such as oilcakes from vegetable oil production or fishmeal from gutting and cleaning. The results show that limiting livestock production to leftover streams can indeed have a positive effect on total food supply, both at the level of individual livestock production systems (van Zanten et al., 2016b) and at the food system level (Röös et al., 2016; Schader et al., 2015). Moreover, a diet with a limited amount of animal products supplied from livestock limited to leftovers uses less land than entirely plant-based diets (van Zanten et al., 2016a).

Although the concept of using leftovers for animal feeding is appealing and straight-forward at first glance, it is not always clear which resources can be considered leftovers. Previous studies have highlighted some aspects of this complexity. For example, Mottet et al. (2017) estimate that around 35% of global permanent pastures are potentially convertible to cropland, and thus not a leftover. Methods have also been developed to assess which food processing co-products and by-products drive land use and which do not, often based on economic value (e.g. Dalgaard et al., 2007).

However, there are additional factors which need to be taken into account. For example, complete exclusion of livestock from arable soils could result in cessation of forage crop cultivation and a risk of sub-optimal crop rotations for building and maintaining soil carbon (Poeplau et al., 2015), preventing weeds (Bachinger and Zander, 2007) and supplying nitrogen (Carlsson and Huss-Danell, 2003). This is especially crucial in low-input organic farming systems, which are being advocated in order to address many of the sustainability issues of current farming practices and are projected to be of increased importance for future food systems (Reganold and Wachter, 2016). Organic farming systems often rely on mixtures of grass and leguminous forage crops in the rotation (referred to as grass-legume leys) for e.g. nitrogen input and weed control (Bachinger and Zander, 2007). In such systems a part of the productive area is “sacrificed” to fertility building crops not directly usable for food, thus increasing overall land use but potentially improving sustainability according to other indicators (Röös et al., 2018). These crops can either be ploughed down (i.e. green manure) or harvested for animal feed or bioenergy. Forage produced in these systems can thus be considered a non-determining by-product of crop production (i.e. not driving land use and other environmental impacts) and thus a leftover resource available for livestock feeding without competing with food production. Similarly, other crops grown between food crops to ensure healthy crop rotations can also be considered leftovers of the cropping system. When the use of chemical inputs is restricted, well-designed crop rotations are indispensable to prevent soil-borne disease pressure, which can be a problem if e.g. oilseed crops or grain legumes are grown too frequently (Robson et al., 2002). At the same time, these crops are important to maintain dietary fat and protein for humans when animal products are limited in diets. We therefore propose the concept of ‘cropping system leftovers’ to account for the need for healthy crop rotations that facilitate future sustainable farming systems.

In this study, we modelled how different utilisation of leftover streams affects food production, land use, GHG emissions and nutrient flows in future food systems based on organic agriculture. We used as a case two scenarios for future food systems in Denmark, Finland, Norway and Sweden (referred to here as the Nordic region). In both scenarios, livestock were limited to non-food competing feed, but entailed different approaches to leftovers and their use. In the first scenario, ruminant animals were limited to the minimum number needed to graze all semi-natural grasslands in the Nordic region, while in the second scenario the number of ruminants was allowed to increase to make full use of forage crops grown in the organic crop rotations. Our aim with the study was to add knowledge on the concept of livestock fed with non-food competing feed and illuminate important aspects previously not discussed in the scientific literature. Such knowledge is needed for developing effective future policy that strives to achieve sound use of agricultural land and limit the negative environmental impacts of food systems.

2. Methodology

The Nordic countries are situated in northern Europe, mainly on the Fennoscandian peninsula between approximately 55 and 70 °N. All the Nordic countries have a highly developed globalised food system that is currently reliant on imports from Europe and the rest of the world in terms of energy, fertilisers, food products and animal feedstuffs in order to sustain current resource-intense eating patterns, for example consumption of meat in the Nordic countries is approximately double the global average (FAO, 2018). Only Denmark has net export of agricultural commodities, due to a prominent pig industry exporting both meat and live animals. However, the self-sufficiency ratio of cereals and starchy roots is relatively high for all countries in the region except Norway. Table 1 provides a summary of agriculture in the Nordic region.

2.1. Scenario development

The scenarios we used to illustrate the different approaches to leftover streams were co-developed through a participatory approach with several non-government organisations (further described in Karlsson et al., 2018) and were based on a Nordic food vision where the majority of food is produced regionally through organic farming practices and livestock limited to non-food competing feed. The scenarios also had to integrate the food system with the energy system by allocating leftover streams to both livestock feed and bioenergy production, supplying all on-farm energy needs and making agriculture self-sufficient in energy, which is thus a binding condition for the modelled food systems.

A diet meeting the Nordic nutrition recommendations and resembling current eating patterns suggested by the Swedish National Food Agency (Enghardt-Barbieri and Lindvall, 2003) was used as a baseline diet. This diet contains 9830 kJ or 2350 kcal (1 kcal ≈ 4.2 kJ) of energy per day, of which 26% is supplied from fat and 16% from protein, and a total of 2470 kJ (~25%) of animal-source foods, while the rest is plant-based. In the scenarios, arable land was first allocated to grow the plant-based part of the baseline diet. All animal-source products were excluded and replaced with animal-source food produced from livestock systems limited to non-food competing feed under two different scenarios, Sufficiency (SY) and Efficiency (EY). In the SY scenario, livestock and aquaculture production were limited to food processing by-products and the number of ruminants needed to graze all semi-natural pastures. This reflected the view that there are alternative uses of the biomass produced by ley cultivation, e.g. as green manure, bioenergy or biomaterial production. In the EY scenario, animals were included to utilise all biomass from leys, i.e. food production from arable land was prioritised over other uses of land. Plant-source foods that cannot be

Table 1
Summary statistics on agriculture in the Nordic region. Agricultural area and cereal yields are according to national statistics organisations in each country. Self-sufficiency ratio, N fertiliser application and energy use is calculated from FAOSTAT data for the years.2010–2012.

	Denmark	Finland	Norway	Sweden	Nordic region
Population *(millions)*					
2015	5.7	5.5	5.2	9.8	26.2
2030 (projected)	6.0	5.7	5.9	10.8	28.4
Agricultural area *(million ha)*	2.6	2.3	1.0	3.1	9.0
per capita *(ha/cap)*	0.47	0.41	0.19	0.31	0.34
Average cereal yield *(kg dry matter/ha)*	5.1	2.9	4.0	4.8	4.3
Self-sufficiency ratio* *(%)*	108	107	59	111	103
Use of agricultural area *(% of total agricultural area)*					
Arable land	92	92	82	85	89
Cereals	56	52	30	31	43
Rapeseed	6.2	2.3	0.6	3.4	3.6
Grain legumes	0.4	0.8	0.0	1.5	0.8
Ley and pastures on arable land	21	31	49	39	33
Semi-natural pastures	7.8	7.9	18	15	11
N fertiliser application *(kg N/ha arable land)*	75	72	112	62	74
Electricity use in agriculture *(PJ/year)*	4.8	3.9	5	2.6	16
Fossil fuel use in agriculture *(PJ/year)*	27	18	27	9.0	81

* Self-sufficiency ratio = Domestic production over domestic supply of cereals and starchy roots with 1 kg starchy roots = 0.26 kg cereals, as defined by Michael et al. (2015).

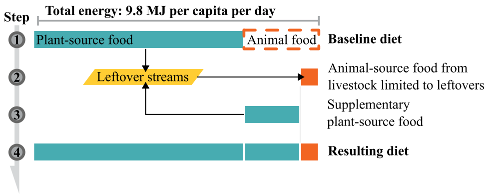

Fig. 1. Schematic illustration of the methodology used for calculating the scenario diets. 1) Arable land is allocated to produce the plant-based part of the baseline diet. 2) Depending on the scenario, leftover streams (grass from semi-natural pastures and outfield areas, biomass from leys in the organic crop rotations, feed grain and food processing by-products) are fed to livestock producing animal-source food. Cultivated leys (and feed grain) require additional arable land. 3) The 'missing' energy from the baseline diet is supplemented with plant-source food grown on arable land. The supplementary plant-source food generates additional leftovers available for animal feeding. 4) The resulting diet is a combination of the fixed plant-based fraction from the baseline diet and animal-source food from livestock limited to leftovers plus additional plant-source food to supplement missing protein, fat and energy.

grown in the Nordic countries (e.g. tropical fruits, tea and coffee) were assumed to be imported. However, these foods make a limited contribution to the total diet of around 290 kJ per day (~3%). In addition, an 'equitable' amount of wild-caught fish was included in the diets, based on projected global fish supply in 2030 (Msangi et al., 2013) divided by the global population, which resulted in 27 kJ wild-caught fish per day. The energy gap between the animal-source food in the scenarios and in the baseline diet was met using plant-based sources of carbohydrates, proteins and fats (Fig. 1).

2.2. *Leftover streams*

Leftover streams were used for animal feed to varying extents in the two scenarios, as summarised in Table 2 and described in Sections 2.2.1–2.2.3. Apart from leftover streams used for animal feed, food and slaughterhouse wastes, straw, manure and biomass from leys were used as bioenergy substrate, bedding material and biological fertilisers in the scenarios. Manure collected in animal houses, biomass from leys and wastes were digested to produce biogas which was used for cogeneration of heat and electricity and partly upgraded for use as fuel for agricultural machinery. Straw was burned for heat. Please refer to Karlsson et al. (2017) for specifics and data sources used.

2.2.1. *Semi-natural pastures and outfield areas*

Semi-natural pastures, generally hosting high biodiversity and where annual cropping is unfeasible or highly challenging, were included and fully utilised in both scenarios. In the SY scenario, the number of ruminants (cattle and sheep) was limited to the minimum number of animals needed to graze all semi-natural pastures. In total, semi-natural pastures occupy some 1.0 million hectares, or 11%, of the total agricultural area in the Nordic countries. In Norway, pastures in alpine and forested areas, referred to as outfield areas, are an important part of the country's animal husbandry (Rekdal, 2013) and these were included as a feed source for cattle and sheep in the Norwegian EY scenario.

2.2.2. *By-products and waste*

Food losses throughout the food chain were accounted for using waste factors taken from Gustavsson et al. (2011) for different commodity groups. In line with the United Nations Sustainable Development Goals, avoidable food waste at the retail and consumer stages was assumed to be half the current level. A waste hierarchy was applied to all wastes generated; recoverable losses at the processing, storage and distribution stages fit and legally allowed for animal feeding (referred to as food processing by-products) were assumed to be fed to animals, all other food losses and wastes (with recovery of 80%) were assumed to be digested for bioenergy together with manure and biomass from leys, and the remaining wastes were assumed to be lost from the food system.

2.2.3. *Grass-legume leys and feed grain*

The amount of grass-legume leys cultivated in the scenarios was determined in two steps. First, one-third of grass-legume leys was included in the crop rotations, justified by the need for biological nitrogen fixation and also for preventing problems with weeds in the absence of pesticides (Bachinger and Zander, 2007). This is slightly more than the 24% global average inclusion in organic crop rotations reported by Barbieri et al. (2017). If needed, more ley (i.e. exceeding the one-third) was included in the crop rotations to limit the frequency of rapeseed and grain legume cultivation to once every six and 10 years respectively. This was motivated by the need to avoid build-up of pests and soil-borne pathogens, which may affect these crops if grown too frequently (Robson et al., 2002), and based on the assumption that not all arable land is suitable for grain legume cultivation. The climate in

Table 2
Summary of the different leftover streams included in the model. The utilisation of outfield areas, grass-legume leys and feed grain differed between the two scenarios, Sufficiency (SY) and Efficiency (EY), while the other leftover streams were utilised in the same way in both scenarios.

Leftover stream		Sufficiency (SY)	Efficiency (EY)
Land use leftovers	Semi-natural pastures	All semi-natural pastures grazed by cattle and sheep.	
	Outfield areas	Not utilised.	Utilised in Norway, as long as winter feed production for grazing animals does not compete with food production.
Cropping system leftovers	Grass-legume leys	Partly utilised for winter feeding of animals grazing semi-natural pastures and for bioenergy. Additional ley biomass is left on the fields to build soil carbon and provide nitrogen.	Fully utilised through grazing, winter feeding and bioenergy production.
	Feed grain	No feed grain cultivated.	Included in crop rotations as long as it does not compete with food production.
By-products and waste	Food processing by-products	Fully utilised for animal feeding.	
	Food waste	Utilised for bioenergy with recovery of 80%.	
	Straw	Partly utilised for bedding and bioenergy.	
	Manure	Utilised for bioenergy and as fertiliser.	
	Biogas digestate	Utilised as fertiliser.	

northern parts of the Nordic countries also limits cultivation of these crops, due to harsh winters and short growing seasons. Based on national statistics on cultivation areas and crop yields, we assumed that no cultivation of rapeseed and grain legumes would take place on arable land situated north of approximately 63 °N, although this might change with future temperature increases due to climate change.

The cultivated leys in the SY scenario were assumed to be utilised as winter feed for ruminants grazing semi-natural pastures, to provide roughage for pigs and to produce bioenergy. Excess ley biomass was left on the fields in this scenario, building soil carbon and providing green manure. In the EY scenario, the number of ruminant animals was allowed to increase to make full use of the biomass from leys and feed grain grown on arable land was included in the crop rotations, replacing some of the ley. Feed grain was only included in the rotations when it resulted in increased food output compared with cultivating ley on the same area (as was the case in the SY scenario).

2.3. Model and impact assessment

A revised version of the food system mass-flow model, further described in Karlsson et al. (2017) and first presented in Röös et al. (2016), was used to model the impacts on the environment and food production. The model is subdivided into four main subsystems (arable land, livestock and aquaculture, bioenergy production, and food processing and consumption) including five animal systems (cattle, sheep, pigs, poultry and aquaculture), 16 crop groups and 32 food items. The environmental impacts assessed were climate impact (measured as global warming potential, GWP_{100}) (IPCC, 2013), eutrophication potential (EP) and acidification potential (AP) (Guinée, 2002). The system boundary was drawn at the farm gate (at shoreline for fisheries and at the national border for imported food) and thus emissions from post-farm processing, storage and transport of food were not considered. Energy use on farms and fisheries was accounted for. Biomass (manure, wastes, ley biomass and straw) was allocated to produce bioenergy used in animal houses and for agricultural machinery, while diesel was assumed to be used for the fishing vessels. A more detailed description of the model and input data can be found in Karlsson et al. (2017).

Carbon stock changes in arable soils were assessed for the case of Sweden only due to limitations in data availability and are presented separately from other greenhouse gas emissions. The *Introductory Carbon Balance Model* (Andrén et al., 2004) was used to model arable soil carbon stock changes relative to a 'business as usual' scenario with current land use and animal numbers. Stock changes were calculated over a 100-year timeframe for consistency with estimated GWP_{100}. Carbon sequestered in standing biomass was included for apple orchards and was estimated at 2.0 ton CO_2e per hectare and year over a 100-year timeframe based on sequestration rates reported in Wu et al. (2012). For further details please refer to Karlsson et al. (2017).

National statistics on crop yields, factored with literature values for the yield gap between conventional and organic farming (de Ponti et al., 2012), were used to calculate the area needed to produce all crops in the scenarios. The yield gap differs between different crops and was applied per crop group in the model, but on average the organic yields were 20% lower. The yields of grass-legume leys were assumed to be 70% higher than reported in national statistics. This was based on data from Swedish ley field experiments and justified by current ley management often being sub-optimal and the harvest often partly being salvaged through grazing, which is not covered by the national statistics. For more details, see Karlsson et al. (2017).

Fertiliser requirements (of nitrogen (N) and phosphorus (P)) for each crop were established through a soil nutrient balance calculation, accounting for biological nitrogen fixation in legumes, atmospheric deposition (regional average), harvested crops and straw, leaching (national averages), denitrification and ammonia volatilisation. Manure and digestate and ash from bioenergy production were assumed to be returned to arable soils, partly meeting the fertilisation requirements. Further nutrient inputs needed were included in the model as an 'unknown external source' and presented as N and P deficits in the results. Further details are provided in Appendix A, Supplementary material.

Five livestock systems were considered in the model: i) Low-yielding dairy systems extensively using pasture resources and producing meat from culled cows, male calves and heifers not entering milk production, ii) autumn lamb production rearing lambs on pastures during the summer, iii) organic pork production with access to pastures on arable land, iv) dual-purpose poultry producing eggs and also meat from culled hens and male chickens, and v) land-based aquaculture using Nile tilapia, a species that can be reared on exclusively plant-source feed (Goda et al., 2007). The herd structures and allocation of feed resources between species were found using a non-linear optimisation algorithm (the generalised reduced gradient method). Constraints were set according to specific livestock feed requirements based on current nutrition recommendations for different livestock species (further described in Karlsson et al., 2017) and the model was optimised for maximum total food output (measured as number of complete diets) based on the available resources in each scenario. This involved finding the feed rations and animal numbers that produce as much animal-source food products as possible from the available leftover streams, in order to minimise the amount of additional land needed for cultivation of supplementary plant-source foods.

The maximum number of people that could be provided with a complete diet was modelled for each Nordic country separately and the totals were then aggregated to a Nordic case.

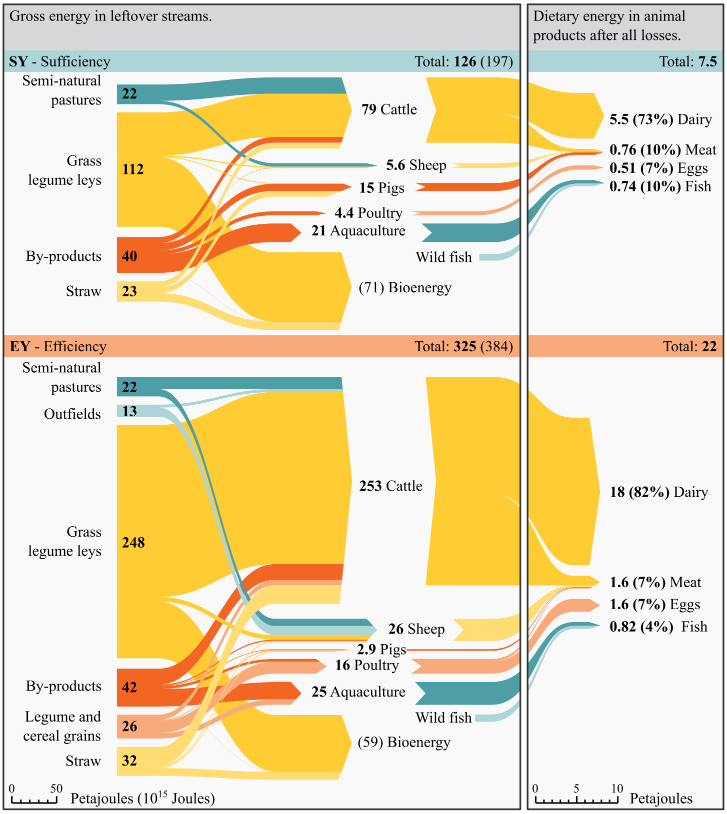

Fig. 2. (Left) Total supply of gross energy from leftover resources and their allocation to different livestock species and to bioenergy and (right) total contribution of dietary energy from different animal products. Offal and blood are excluded from the diagram, but contributed 0.08 and 0.20 PJ in the SY and EY scenario diet, respectively. Line width is proportional to energy, but note the different scales on the left and right sides of the diagram. Note also that "Bioenergy" represents the gross energy in leftover streams (excluding wastes) used as feedstocks which does not equate to energy in produced biogas.

3. Results and discussion

3.1. Food production and resulting diets

It was estimated that complete diets for 30.9 and 37.0 million people could be produced in the SY and EY scenario, respectively, which is 2.5 and 8.6 million more than the projected population of the Nordic region in 2030. If reductions in food waste (i.e. halved waste levels at the retail and consumer stage) could not be achieved, the need for arable land would increase by around 13–14%. Both scenarios led to diversified crop rotations where e.g. cereals occupied one-third (SY) or half (EY) of the current cereal area, grain legume area grew three- to four-fold, as did vegetable cultivation, while sugar beet was cultivated on around half the current area. The extended use of leftovers in the EY scenario allowed for a 20% increase in total food output compared with the SY scenario. Total supply of gross feed energy to livestock more than doubled between the two scenarios, from 126 (SY) to 325 (EY) petajoules (PJ) (Fig. 2). The main increase was from inclusion of biomass from leys left as green manure in the SY scenario, which accounted for 75% of the increase. The inclusion of feed grain in crop rotations to limit grain legume and rapeseed cultivation accounted for 13% of the increase, adding 26 PJ of gross energy. In both scenarios, the majority of feed energy was from grass-legume leys. In the EY scenario, 75% of the livestock feed was from leys, while semi-natural pastures and outfield areas together accounted for 11% of feed energy. This shows that organic agriculture relying on N fixation through leguminous forage crops leads to considerable leftover streams that need to be accounted for in food system models of organic farming, a conclusion that is likely to be generalisable beyond the specific geographical context assessed here. At the same time, the amount of grass-legume leys included in our scenarios did not satisfy soil nutrient balances, but left N deficits in both scenarios (further discussed in Section 3.4).

Compared with current consumption patterns, both scenarios involved large changes in the diets consumed. Meat consumption (including poultry) decreased by on average 90 and 81% for the SY and EY scenarios, respectively. This shows that even when assuming a farming system generating substantial amounts of leftovers (i.e. organic agriculture reliant on forage legumes) and irrespective of how these leftovers are utilised, limiting livestock to leftover streams results in a considerable reduction in meat consumption. This is in line with findings in previous studies (Röös et al., 2016; Schader et al., 2015). As leftover streams in the scenarios predominantly consisted of grass resources, the reduction in meat consumption was strongest for non-ruminant meat (-94 and -97% in SY and EY, respectively) while proportionally more ruminant meat remained, especially in the EY scenario diet (-80 and -44% in SY and EY, respectively). Since no specialist beef production units were included, a large proportion of the ruminant feed resources was routed to dairy products, giving a milk supply in the EY scenario approximately equal to current consumption. In the SY scenario, milk consumption was 63% lower than current levels. By utilising all leftovers arising from the organic farming system, the EY scenario could supply an additional 6 million people with a diet containing around twice as much meat and almost three times as much dairy as in the SY scenario.

The differing composition of leftover streams in the two scenarios also affected the composition of the resulting diets. In the SY scenario, poultry was limited by the suitability of available by-products as poultry feed, favouring pigs in this scenario. The protein-energy ratio in many of the by-products was high, making it difficult to supply enough energy in poultry feed without exceeding the recommendations on crude protein of around 15% for laying hens (NRC, 1994). In the EY scenario, feed grain with a lower protein-energy ratio was largely allocated to poultry, due to their favourable feed conversion ratio. By-products allocated to pigs in the SY scenario were allocated to ruminants in the EY scenario, thus reducing the number of pigs. The animal feed rations were in this study formulated based on species-dependent requirements and limitations on energy, protein and fat, while specific amino acid and micronutrient composition was not assessed. However, in order to ensure feasible rations for poultry, a minimum inclusion of by-product fishmeal was set at 0.2 kg dry matter per head and year (equal to around 0.5% and 2.4% of layer and cockerel diets). However, ensuring an adequate supply of amino acids and micronutrients for monogastric animals based on available by-products could prove difficult, given that the use of e.g. synthetic amino acids is currently not permitted in organic animal production.

Both scenario diets were at the lower end of (but compliant with) the Nordic nutrition recommendations for dietary fat and protein, but exceeded the recommendation for carbohydrates. Due to reduced consumption of animal fats and exclusion of imported oils, the regional production of vegetable oil needed to increase considerably in the scenarios, and therefore also the area cultivated with oilseed crops. Compared with the current situation, a threefold increase was observed for both scenarios. Since rapeseed cultivation is not feasible in northern parts of the Nordic region and due to the risk of soil-borne diseases if rapeseed is grown too frequently, the system was found to be limited by the amount of oilseed crops able to fit into the organic crop rotations. To limit rapeseed cultivation, the area of ley reached 48% of arable land in the SY scenario, of which only 28% was utilised for feed or energy. The maximum number of diets that could be produced was thus governed by the amount of vegetable oil needed in the diets. More animal-source fats in the EY scenario led to less vegetable oil needed and thus the total area that could be cultivated with food crops increased from around 3.8 million hectares in the SY scenario to 4.9 million hectares in the EY scenario. Reducing the amount of vegetable oil in the diets was not a viable option, since the scenario diets were already at the lower end of the recommendation for dietary fat. Thus the capacity of the food systems to supply enough fat in the diets was found to be limiting, while protein, which is commonly the focal point in the discourse on low meat and dairy diets, was found not to limit system productivity. This highlights the importance in food system modelling studies of including cropping system limitations, together with nutritional requirements that go beyond dietary energy and protein. While the Nordic region provides a specific context in terms of e.g. plausible organic crop rotations, assessing organic farming systems will require similar considerations irrespective of geographic context.

3.2. Bioenergy

In total 49 (SY) and 60 (EY) PJ of biogas was produced, of which slightly more than half was used for cogeneration of heat and electricity and the rest was further upgraded for use as vehicle fuel. 10 (SY) and 9.3 (EY) PJ of straw was also burned for heating greenhouses and stables. The current use of fossil fuels in the Nordic agricultural sector (excluding fisheries) is around 81 PJ (Table 1). Total use of electricity was 53% (SY) and 36% (EY) lower in the scenarios compared with current levels, mainly due to reduced animal housing requirements. In the SY scenario 52% of biogas was produced from leys, while in the EY scenario, although using more energy in total, the need for bioenergy production from ley biomass was reduced due to increased availability of manures and wastes as feedstock. In this scenario, 35% of biogas was generated from harvested ley biomass.

3.3. Land use and environmental impacts

The agricultural land requirement in the Nordic countries to produce the SY and EY scenario diets was estimated at 0.26 and 0.21 ha per diet, respectively, of which 13% was semi-natural pastures and the rest arable land. Making use of all leftovers for livestock feeding in the EY scenario enabled grass-legume leys and some grain from leftover arable land to be turned into animal-source food, and thus reduced the area needed to grow plant-based supplements compared with the SY scenario. In addition to land used in the Nordic region, 0.01 ha was needed outside the region to produce the imported food. Of the total arable land, 7% was used for livestock feed cultivation and pastures on arable land in the SY scenario and 37% in the EY scenario.

The annual climate impact of the scenario diets was estimated at 0.36 and 0.48 ton CO_2e per diet for the SY and EY scenario, respectively. Methane from enteric fermentation accounted for 28% (SY) and 57% (EY) of the climate impact, soil nitrous oxide emissions for 45% (SY) and 21% (EY), and the rest was divided between imported food, manure management, bioenergy production and use, and fossil fuel combustion on fishing vessels. The larger climate impact in the EY scenario was due to the larger number of livestock, especially ruminants, which increased from 1.3 to 4.1 million cattle and from 0.9 to 4.4 million sheep to make use of all grass resources. The difference between the scenarios was somewhat counterbalanced by larger emissions of nitrous oxide in the SY scenario due to substantial N inputs to croplands in the form of green manure.

Eutrophication potential was largely driven by leaching of N and P from arable soils, contributing 72% (SY) and 67% (EY) of the EP. Due to the larger food output in the EY scenario, the EP per diet was lower than in the SY scenario. However, when emissions were presented per hectare the relationship was reversed due to larger ammonia emissions in the EY scenario, contributing 32% of EP compared with 28% in the SY scenario. The rate of N and P losses due to leaching was estimated based on average values per hectare presented in national statistics, which represent the current situation and do not account for changes due to adoption of organic agriculture. Low-input organic agriculture generally results in reduced leaching of soil nutrients on a per hectare basis compared with conventional farming, but there are large variations (Seufert and Ramankutty, 2017).

Acidification potential in the scenarios was almost exclusively dependent on volatilisation of ammonia. In the EY scenario, storage of digested manures and wastes accounted for most of the emissions, while in the SY scenario grass-legume leys left as green manure accounted for considerable ammonia emissions, contributing 35% of the acidification potential.

Even though livestock in the EY scenario required a larger share of total arable land, this scenario performed better in terms of land use efficiency than the SY scenario, increasing the total food output per hectare by 20% and increasing the supply of animal-source food almost threefold (Table 3). However, less livestock in the SY scenario led to

Table 3
Annual impacts on food supply, land use, climate, eutrophication, acidification and soil nutrient deficits in the two scenarios, expressed per diet produced and per hectare Nordic arable land.

Impact	Units	Per diet produced			Per hectare arable land		
		SY	EY	SY → EY	SY	EY	SY → EY
Food supply							
Total food output	*1000 MJ*	3.6	3.6	*+0%*	16	19	*+20%*
Animal-source food	*1000 MJ*	0.25	0.59	*+141%*	1.1	3.2	*+189%*
Environmental impacts							
Land use	*ha*	0.27	0.23	*−16%*	1.2	1.2	*+1%*
Arable land use	*ha*	0.22	0.19	*−16%*	1.0	1.0	*+0%*
Climate	*ton CO_2e*	0.36	0.48	*+32%*	1.6	2.6	*+58%*
Eutrophication	*kg $PO_4^{3-}e$*	3.2	2.9	*−9%*	14	16	*+9%*
Acidification	*kg SO_2e*	5.6	5.9	*+6%*	25	32	*+26%*
Soil nutrients							
N-deficit	*kg N*	3.5	3.9	*+11%*	16	21	*+33%*
P-deficit	*kg P*	0.8	0.9	*+6%*	3.8	4.8	*+27%*

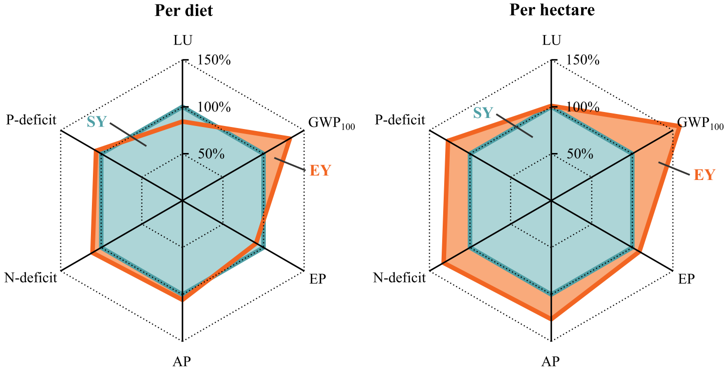

Fig. 3. Comparison of the impact of the two scenarios on land use (LU), climate (GWP_{100}), eutrophication (EP), acidification (AP) and soil nutrient (N- and P-) deficits, expressed (left) per diet and (right) per hectare of Nordic arable land. Impacts are presented relative to the SY scenario (= 100%).

better GHG efficiency, with a lower climate impact per diet produced. This indicates a trade-off between optimising the food system for land use (i.e. feeding as many as possible) and reducing GHG emissions from food production (Fig. 3). Clover-grass biomass was primarily fed to ruminant animals in the scenarios, which therefore favoured cattle and sheep over pig and poultry. However, recent developments in biorefinery processes have enabled the production of high quality protein feeds suitable for monogastric animals from green biomass (Santamaría-Fernández et al., 2017). Using such systems to feed grass biomass to monogastric animals could increase the feed use efficiency of the system and reduce methane emissions, thus potentially alleviating the above-mentioned trade-off between land use and GHG efficiency.

Including more environmental impact categories showed that increased utilisation of leftovers for livestock feed had a positive influence on EP, which was lower in the EY compared with the SY scenario. On the other hand, more livestock led to an increase in AP due to larger ammonia emissions. Considering that EP and AP are impacts that primarily affect the local environment, whereas climate impacts act on global scale, it may be more relevant to compare emissions on a per hectare basis for EP and AP. In that case the SY scenario performed better in all environmental impact categories, but it must then be considered that the additional 6 million diets supplied in the EY scenario would need to be produced somewhere else.

For the Swedish case, it was estimated that arable soils and standing biomass sequestered 93 kg CO_2 per diet and year in the SY scenario, while in the EY scenario losses of soil carbon resulted in net emissions of 28 kg CO_2 per diet and year, which further exacerbated the difference in climate impact between the two scenarios. Soil carbon losses in the EY scenario were mainly due to reduced yields compared with the current situation, while in the SY scenario low yields were counterbalanced by substantial input of biomass to soils in the form of green manure. This contradict previous results in e.g. Gattinger et al. (2012), where organic farming was shown to increase topsoil carbon. This can mainly be explained by current Nordic crop rotations already being similar to organic rotations, i.e. including grass and grass-legume leys to a degree similar to that in the scenarios. Thus, the lower yields in the scenarios resulted in lower carbon inputs to soils.

3.4. Nutrient flows and soil nutrient balance

Tracking nutrient mass flows (Fig. 4) revealed that a total of 92 (SY) and 124 (EY) kg N per hectare was removed from arable soils every year through crop harvest and losses. Nitrogen fixation in legumes, deposition and recirculation of nutrients from manure and food waste could cater for around 80% of the removals, leaving 16 (SY) and 21 (EY) kg N per hectare unaccounted for. Utilising all ley biomass for livestock feeding in the EY scenario led to increased losses of N throughout the ‘animal loop’, mainly in the form of ammonia from management of manure and biogas digestate. However, these losses were offset by a clear reduction in ammonia volatilisation from crop residues compared with the SY scenario. Denitrification losses were also

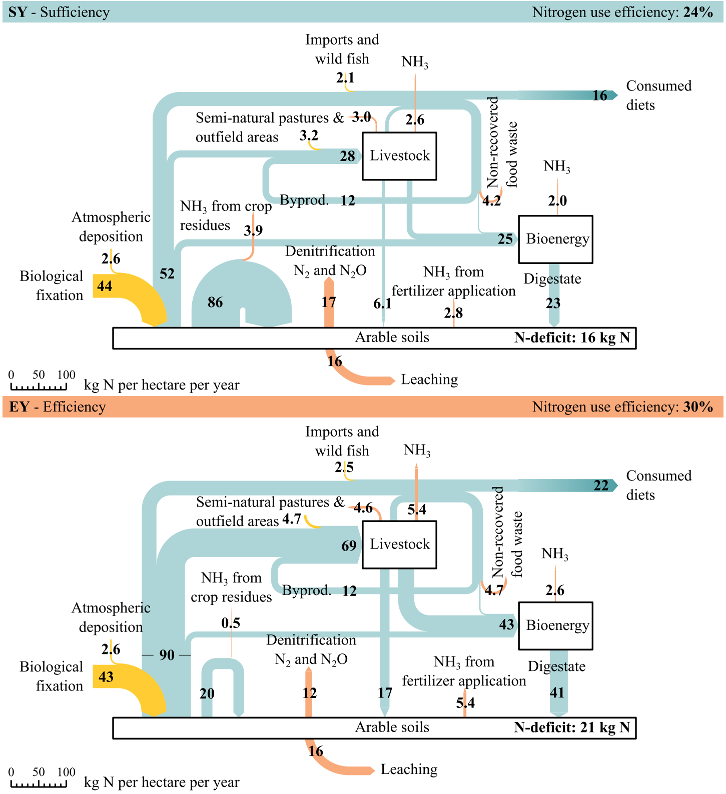

Fig. 4. Estimated nitrogen (N) flows throughout the modelled system. Line width is proportional to flow magnitude. Yellow lines represent N entering the system, blue lines show intended N flows within the system and red lines show unintended flows to the atmosphere, water bodies or waste streams not returned to arable soils. Nitrogen use efficiency is defined as the sum of N entering the system divided by N in the diets consumed. 'N-deficit' is the additional amount of N needed to balance the system (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

higher in the SY scenario, due to higher annual N inputs to soils, while in the EY scenario more N was harvested and subsequently lost to a larger extent, either as ammonia or as protein in the consumed diets.

The overall losses of N from the system (excluding N in diets consumed) were similar for both scenarios, but the larger total food output in the EY scenario resulted in a larger N deficit compared with the SY scenario. On a per diet basis, however, losses were larger in the SY scenario. For the long-term sustainability of the cropping system, the N deficits would need to be met by further nutrient inputs. The diets consumed annually contained the equivalent of 16 and 22 kg N per hectare in the SY and EY scenario, respectively. These nutrients could partly be recovered from human excreta, but other external N sources, or further increased cultivation of leguminous crops would also be needed. Only between 5% and 10% of N fixation in the scenarios was in human-edible grain legumes, even though the area devoted to their cultivation was around 100% (SY) and 240% (EY) larger in the scenarios than in the current situation in the Nordic countries. The majority of N fixation was thus performed in forage legumes. In fact, our results indicate that more legume-based forage crops would be needed for a sustainable N supply on converting to organic production on a large scale. This supply could potentially come from the use of cover or catch crops incorporated into the cropping system, thus not affecting the output in terms of food. These results show the importance of leguminous forage crops in cropping systems that rely on biological N fixation, and thus also the need to consider the best use of this non-human edible biomass.

In 2015, each hectare of arable land in the Nordic region received on average 82 kg N of synthetic fertiliser. Assuming no recovery of human excreta, 21% (SY) or 28% (EY) of this application rate would be needed to cover the N deficits. Together with recycling from human excreta, this could potentially be supplied by allowing the use of synthetic N fertilisers produced from renewable sources (Ahlgren et al., 2010). This is currently not allowed under organic regulations, but the need to allow for some mineral fertilisers in organic production has been highlighted in other studies and might be a plausible option as organic regulations develop (Röös et al., 2018).

Flows of P throughout the system were also modelled and resulted in a soil P deficit of 3.8 (SY) and 4.8 (EY) kg P per hectare and year. The consumed diets contained 2.3 (SY) and 3.2 (EY) kg P per hectare, which could potentially be recovered but, as with N, other external sources would likely be needed to avoid losing soil fertility. Currently, P supply to organic farms is heavily dependent on imports from conventional farms in the form of e.g. manure. Nowak et al. (2013) estimated that as much as 73% of the P input to French organic farms actually originated from conventional farming, making organic farming indirectly highly dependent on conventional mineral fertilisers. New innovative sources of P that can close nutrient loops by e.g. recovering P from agricultural runoff or returning P containing biomass from sea to land are therefore needed to minimise the reliance on mined phosphate rock (Roy, 2017; Spångberg et al., 2013).

4. Conclusions

This analysis showed that organic agriculture in the Nordic region could supply a large population with complete diets when combined with reduced food wastage and dietary changes following from livestock production limited to leftover streams. Comparisons of sufficiency (SY) and efficiency (EY) scenarios showed that utilisation of all leftovers (EY) led to increased total food output, and thus reduced land use per diet produced, but that there were goal conflicts that need to be considered when determining how much livestock production is optimal. The SY scenario had both a lower climate and acidification impact per diet produced and also a better soil nutrient balance compared with the EY scenario, and per hectare the SY scenario performed better in all environmental impact categories. Many of these trade-offs are generalisable to other regions and contexts, for example the trade-off between cropland use efficiency and GHG emissions in using ruminants to utilise leftover streams. However, the outcome in terms of composition, number of diets and exact environmental impacts from diets depends largely on the region modelled. By assessing the interplay between limiting livestock to non-food competing feed and organic agriculture, we demonstrated that three principally different types of leftovers arise: i) Land use-related leftovers, i.e. biomass from areas where annual cropping is unfeasible, ii) by-products and wastes from food production, processing and consumption, and iii) cropping system leftovers that arise from the need for crop rotations that maintain soil fertility especially considering, as here, low-input organic farming systems, but the concept is also relevant for other types of cropping systems. We show that a considerable cropping system leftover stream available for ruminant animals in particular arises from the need for including grass-legume leys in organic crop rotations for biological N fixation and weed control. Our results also indicate that N supply would be challenging in the envisaged organic scenarios and that even more leguminous forage crops would likely be needed (if use of synthetic fertilisers is not considered). This biomass is currently only usable for animal feed or bioenergy. Furthermore, based on dietary requirements and accounting for crop rotations suitable in organic farming, vegetable oil was found to limit system productivity, resulting in 'leftover' arable land not usable for plant-source food production, but where feed crops could be cultivated, thus indirectly increasing the supply of animal-source food. Cropping system leftovers thus depend on agronomic limitations in the cropping system, but, as in this latter case, may also be affected by diets and nutritional requirements. Cropping system leftovers have not previously been assessed in studies on limiting livestock to non-food competing feeds, but we show the importance of including detailed descriptions of both agronomic and dietary limitations in order to identify cropping system leftovers and assess the quantity of leftover streams available for animal feed.

In this study, leftovers were primarily fed to livestock and only used for energy to the extent that agriculture was self-sufficient, but it is not clear whether this is the soundest use of these resources. While ruminant animals are able to convert inedible resources into food, thus reducing land use per diet, they come at a climate cost. This study clearly illustrates trade-offs between several sustainability objectives when considering the role of livestock and animal-source food in future food systems. These trade-offs need to be accounted for and weighed against each other in future agricultural and food policies, in order to avoid undermining the essential preconditions for future food security – a stable climate and maintained soil fertility.

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Competing interests

We declare no competing interests.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.landusepol.2019.03.035.

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Halting European Union soybean feed imports favours ruminants over pigs and poultry

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The European Union (EU) livestock sector relies on imported soybean as a feed source, but feeding soybean to animals leads to a loss of macronutrients compared to direct human consumption, and soybean production is associated with deforestation. Here we show that 75–82% of current EU animal fat and protein production could be sustained without soybean imports while avoiding increased use of cropland for feed production within the EU. Reduced soybean feed exports, mainly from South America, would free up 11–14 million hectares outside the EU, but indirect land-use changes would increase demand for palm oil produced in southeast Asia. Avoiding imported soybean feeds would result in reduced EU pork and poultry production; increased plant-based food consumption would be required to maintain the supply of essential nutrients for human diets. Optimizing livestock production to overcome dependency on imported soybean feed can reduce cropland demand in deforestation-prone areas while supporting the nutritional requirements of EU diets—but will require progressive policies targeting all aspects of the food system.

Providing healthy food for a growing human population without further expanding agricultural land is a major global challenge[1,2]. In high-income regions, consumption of meat, milk and eggs is considerably higher than in the rest of the world[3]. To meet demand for animal-source food, the EU relies on imports of protein-rich animal feeds, especially soybean, which constitutes almost one-third of all protein (excluding roughage) used for animal feed in the EU[4]. Soybean trade is associated with agricultural expansion and deforestation, particularly in South America[5–8] (where more than 50% of global soybean is produced[9] and 70% is exported[10]). The EU imports around 21% of these exports[10] for use in animal feed. The soybean crop has outstanding protein yield per hectare, but production often involves environmentally harmful production practices[11,12] and its current predominant use as cheap animal feed is inefficient compared with direct human consumption. As highlighted in the EU's Farm to Fork Strategy[13], agricultural policy reforms must incentivize domestic protein feed production, overcome import dependency and reduce land demand in deforestation-prone regions[14,15].

Previous studies have assessed the market and environmental consequences of replacing imported soybean in Europe with locally produced feeds and by-products. Market studies show that disrupting soybean imports to Europe will increase livestock production costs[16,17] and thereby lead to reduced production of especially pig and poultry products, while ruminant production is less affected[17]. Environmental studies using life cycle assessment (LCA) generally show that using locally produced feed instead of imported soybean would have climate and land-use benefits[18–21]. However, environmental consequences are usually assessed at the farm or production system level, so the consequences of using finite resources such as cropland are not adequately captured. Strategies at the EU level to abolish soybean imports for feed would have broader food-system-level consequences. For example, using by-products to replace soybean (for example, co-products from vegetable oil or bioenergy production) is limited by production of the primary products and many by-products are already fully utilized. Similarly, replacing all imported soybean meal with EU-grown pulses and soybean would increase the share of EU cropland devoted to animal feed production, reducing the area available for growing crops for human consumption. This could unintentionally shift import dependency from feed crops to food crops, increasing land demand elsewhere, with potential negative environmental effects. Moreover, using soybean meal in animal feed is associated with co-production of soybean oil, which is traded on global markets and used for food or biofuel. If soybean meal use ceased, soybean oil would have to be replaced with other oils.

We use a food systems approach to estimate potential production of animal-source food in the EU under three different scenarios with two main constraints: no soybean imports for feed (including all soybean and meal imported directly as well as soybean meal produced within the EU from imported beans) and no additional arable land use for feed cultivation within or outside the EU. We develop a biophysical model to optimize provisioning of human-edible protein under these constraints, by identifying the numbers and types of livestock that utilize available feed resources most efficiently. We then calculate cropland use within and outside the EU and provisioning of essential macronutrients and micronutrients to human diets from the remaining livestock production. We do not consider economic prerequisites or implications of this change—rather, we assess the options for reducing reliance on imported soybean from a purely biophysical perspective, regarding the livestock products and amounts that can be produced in the EU without soybean imports and without using more EU cropland for feed production, and the implications for land use and human diets.

Results

Baseline EU production of meat, milk and eggs. The EU livestock sector converted feed inputs into 190 Mt raw milk, 8.6 Mt beef and

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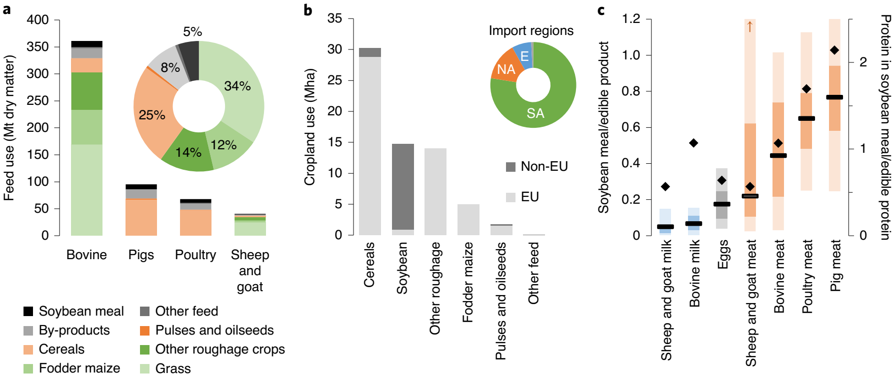

Fig. 1 | Current (2014–2016) use of feeds, cropland and soybean meal in the EU livestock sector. a, Feed dry matter use for EU livestock as harvested products before storage and feeding losses. **b**, Arable land use for feed production inside (light grey) and outside (dark grey) the EU. The segmented circle shows the fraction of non-EU cropland use in South America (SA, green), North America (NA, orange), Europe outside the EU (E, blue) and the rest of the world (RoW, grey). **c**, Soybean meal use for different animal-source foods ($n = 27$ except for sheep and goat milk where $n = 22$). The left axis shows EU-weighted average use of soybean meal per kilogram of edible food product (horizontal lines) and the 25–75th and 5–95th percentiles of EU countries (dark and light vertical bars, respectively). The right axis shows EU-weighted average protein in soybean meal per kilogram of edible protein (black diamonds). Soybean meal was allocated between milk and meat on the basis of the protein content of the edible product.

lamb, 23 Mt pork, 14 Mt poultry meat and 7.1 Mt eggs annually from 2014 to 2016. Feed inputs comprised around 560 Mt dry matter feed annually, of which ~5% was soybean meal (Fig. 1a). Most (77%) of the cropland required to produce feed (mainly cereals and roughage) was within the EU, using around 48% of EU cropland (Fig. 1b). Of the remaining cropland (23%) outside the EU, most was used for soybean production (90%) mainly in South America. Poultry and pig production used more soybean meal per kilogram product than ruminant production (Fig. 1c), with large differences between member states.

Optimizing livestock production to avoid soybean imports. Removing imported soybean from EU livestock diets would leave a pool of EU feed with lower protein. We optimized use of this feed pool by restructuring livestock production in each country in a way that maximizes output of human-edible protein. To maintain an appropriate protein/energy ratio in livestock diets where soybean was removed, some currently used cereals and other energy-rich feeds had to be excluded from the feed pool. This reduced the total amount of feed available for EU livestock—supporting fewer animals—but made EU cropland used to produce these feeds available for other purposes. We accounted for this available cropland in three scenarios (S1–S3; Fig. 2). In scenario S1 (feed crops), soybean and pulses for animal feed were grown on the available land. This scenario shows how much livestock production can be maintained in the EU without soybean imports or additional EU cropland use for feed production, which might cause indirect land-use changes. In scenario S2 (oil crops), vegetable oil was produced on the available cropland to replace soybean oil and imported vegetable oils. In scenario S3 (food crops), soybean, pulses and vegetable oil for direct human consumption were grown on the available land to support transition to more plant-based human diets. The rationale for the scenarios is explored in the Methods.

To make the scenarios comparable, all were assumed to produce equal amounts of human-edible protein and fat, and equal amounts of vegetable oils for the global market (Fig. 2). Additional vegetable oil requirements were assumed to be met by palm oil, the marginal oil in global trade[22], and additional human-edible protein requirements by imported soybean for human consumption.

Using EU cropland for feed crops (scenario S1). Replacing imported soybean with EU-produced soybean, broad bean, pea and lupin, without utilizing more than the 48% EU cropland currently used for feed cultivation, reduced demand for non-EU cropland by 11 Mha (Fig. 3b) and production of meat, milk and eggs by 18% in terms of edible protein and fat. Ruminants can assimilate low-quality feeds, such as grass and other types of forage, and were therefore favoured in the optimization model, maintaining 96% of current production (in terms of edible fat and protein; Fig. 4c,d). Meat from pigs and poultry was reduced by 49% and 34%, respectively (Fig. 4a,b). Egg production was unaffected (Fig. 4e), owing to high output of edible protein relative to feed requirements, making it favourable to allocate high-quality feed to egg rather than pork or poultry meat production. However, as herd/flock sizes were capped at current national levels, egg production did not increase further.

Reduced livestock production would supply less protein, fat and micronutrients for human consumption if not replaced with other foodstuffs. We assumed use of soybean to meet the baseline level of edible protein, which required soybean imports of 7.0 Mt or 3.2 Mt fat + protein (Fig. 3b), equivalent to 17% of current soybean feed imports. As soybean has a higher protein/fat ratio than meat, 1.4 Mt of imported vegetable oil was needed to maintain baseline fat supply. An additional 6.2 Mt vegetable oil was needed for the global market, to replace lost soybean oil production. Demand for non-EU cropland for feed production was reduced by 15 Mha, mainly in South America, where most imported soybean originates, but also in other regions owing to reduced use of imported feed cereals. Soybean and vegetable oil for human consumption required 4.4 Mha cropland outside the EU, leading to demand for 2.0 Mha more cropland in Southeast Asia and Oceania as marginal suppliers of vegetable oils to the global market (Fig. 3b).

In scenario S1, 7.7 Mha of EU cropland (~7% of total EU cropland) currently producing cereals and fodder maize (Supplementary Fig. 3) was cropped with protein-rich feed crops instead (Fig. 3b), constituting a more than fourfold increase from 2.2 Mha to 9.9 Mha.

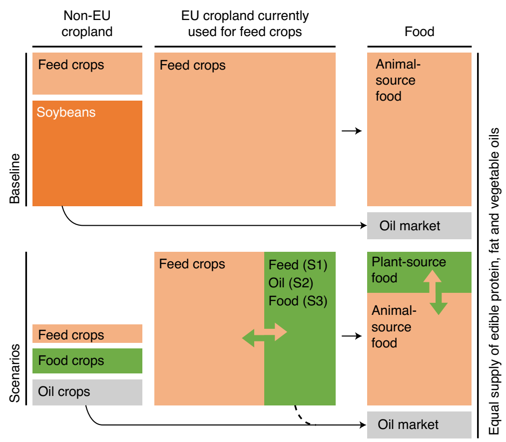

Fig. 2 | A schematic illustration of scenarios for EU livestock production that avoid imported soybean feed and do not increase land use in the EU. Top panel: the baseline scenario (2014–2016) where soybean is imported and used alongside other imported and EU-grown feeds to produce animal-source foods. Use of soybean for animal feed leaves soybean oil, which is traded on the global market and used for food or biofuel. Bottom panel: scenarios in which EU soybean imports for animal feed are cut. This involves removing some energy-rich feeds from livestock diets (to maintain an appropriate protein/energy ratio), which frees up EU cropland. The scenarios consider alternative uses of this spared land to produce protein-rich feed crops (S1), oil crops (S2) or food crops (S3). Each scenario supplies equal amounts of edible protein and fat to the EU population and vegetable oils to the global market from animal- and plant-source (legumes and vegetable oil) foods.

Using EU cropland for oil crops (scenario S2). Replacing imported soybean meal with rapeseed meal, a by-product from increased EU vegetable oil production, reduced demand for non-EU cropland by 12 Mha (Fig. 3c), slightly more than in S1 (11 Mha). The supply of edible protein and fat from meat, milk and eggs was 23% lower than the baseline. Ruminant and egg production were still favoured in the optimization model, but constraints on the maximum amount of rapeseed meal allowed in poultry diets favoured pigs over poultry, leading to a 41% reduction in pig meat and 71% reduction in poultry meat (Fig. 4a,b).

Soybean imports of 8.9 Mt or 4.0 Mt fat + protein (Fig. 3c), equivalent to 22% of current soybean feed imports, were needed to meet baseline levels of protein for human diets. The rapeseed oil produced within the EU was able to supply additional fat to EU diets and global vegetable oil markets, replacing lost soybean oil production. Supply of vegetable oils to global markets slightly exceeded the baseline, giving a small net decrease in demand for non-EU cropland for vegetable oil production.

Cultivation of rapeseed used 7.5 Mha of EU cropland (Fig. 3c), replacing mainly cereals and fodder maize, and doubling the EU area of rapeseed. Cropland demand for soybean and vegetable oil production outside the EU was 3.0 Mha and −0.09 Mha, respectively.

Using EU cropland for food crops (scenario S3). Cultivating plant-source foods on the freed EU cropland gave the greatest reduction in demand for non-EU cropland (14 Mha; Fig. 3d). Domestic production of soybean, broad bean and peas was increased to supply dietary protein to the baseline level, encroaching on cropland currently used for feed production, which reduced animal-source protein and fat supply by 25%. Rapeseed was grown on the remaining cropland to supply vegetable oil to EU diets and global markets. Pig meat production and poultry meat production were reduced by 51% and 68%, respectively (Fig. 4a,b), while ruminant milk production and ruminant meat production were reduced by 5% and 10%, respectively (Fig. 4c,d).

To supply baseline amounts of human-edible protein, 12 Mt or 3.5 Mt fat + protein as soybean, broad bean and peas for human consumption was produced on EU cropland (Fig. 3d). Furthermore, 2.6 and 3.4 Mt EU rapeseed oil were produced for EU diets and global markets, respectively. However, supply of EU vegetable oil to global markets was insufficient to match baseline production of soybean oil, requiring production of 4.3 Mt vegetable oil outside the EU.

Protein-rich food crops and rapeseed were grown on 4.7 Mha cropland each (~9% of total EU cropland), replacing energy-rich animal feed crops. No non-EU cropland was needed for soybean cultivation, but demand for cropland in Southeast Asia and Oceania increased by 1.2 Mha to supply vegetable oil (Fig. 3d).

In all scenarios, pig and poultry diets included less cereals and more pulses and protein-rich by-products to maintain adequate levels of protein and essential amino acids (Supplementary Fig. 2c,d). Ruminant diets generally included more cereals and protein-rich by-products and less maize silage (Supplementary Fig. 2a,b). Cereals replaced maize silage in ruminant diets as their higher protein/energy ratio lowered dependency on protein-rich feeds, increasing utilization efficiency for available feeds.

Effects on human nutrition. In all scenarios, reduced soybean feed imports did not impair supply of most essential nutrients currently provided by animal-source foods (Fig. 5). For most nutrients, the loss due to reduced meat, milk and egg production in scenarios S1–S3 was counterbalanced by the additional plant-source foods (soybean, peas, broad beans and vegetable oil). The exceptions were vitamins A and B_{12}, which were not present or sparingly available in the plant-source foods, resulting in 5–7% and 9–12% reduced supply, respectively, in the scenarios compared to baseline levels.

The supply of individual amino acids to human diets changed by between −13% and +10%, depending on scenario and amino acid (Supplementary Fig. 4). Lysine and threonine were relatively unaffected, while methionine decreased and tryptophan increased on replacing animal-source food with soybean and pulses.

Sensitivity analysis (see Supplementary Information) showed that lifting the constraint on maximum herd/flock size per country would increase animal-protein supply by 38% (scenario S1), but would require dramatic restructuring of the EU livestock sector (for example, increasing egg production fourfold). Lifting the constraint on reallocation of surplus grain (intra-EU trade in feed grain was capped at the baseline level) and increasing the fraction of pig and poultry meat assumed edible had little effect. Allowing more rapeseed meal in pig and poultry diets (anti-nutritional factors in rapeseed limit its use) led to a 6% increase in total edible animal protein (scenario S2) and substantial reallocation of feed from pigs to poultry due to their higher feed conversion ratio.

Discussion

Our analysis, using a biophysical food system model that optimizes use of available feeds under scenarios of ceased soybean imports, showed that ruminants were favoured over pigs and poultry in all scenarios owing to their ability to utilize lower-quality feeds such as grass and other types of forage, making it favourable to reallocate protein-rich feeds from pig and poultry to ruminant production, confirming recent findings[17,23,24]. This contrasts with the common call for sharp reductions in beef and dairy production to reach environmental targets—especially greenhouse gas emissions reductions (for example, ref. [25]). Hence, policies on sustainable livestock

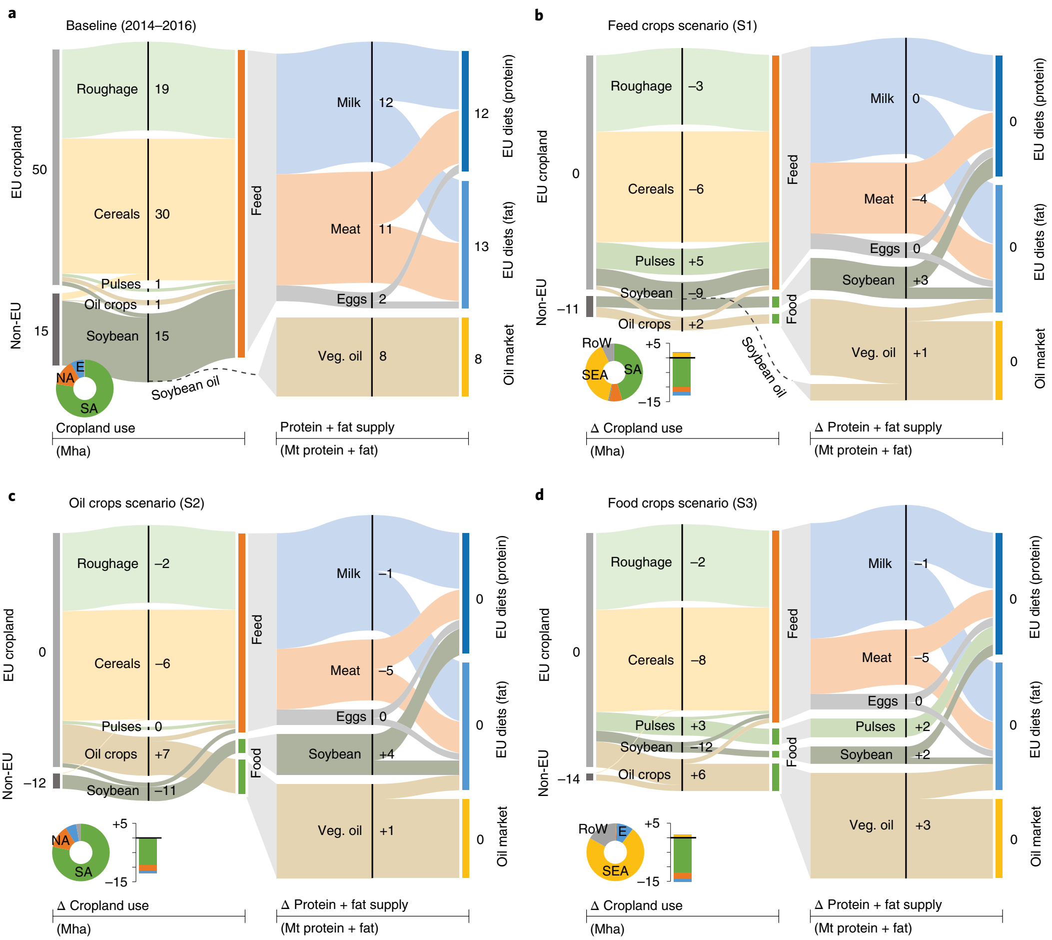

Fig. 3 | Sankey networks showing cropland use for feed and supplementary plant-source foods as well as supply of edible protein and fat from different foods. a–d, Cropland use (Mha; left) and edible protein and fat supply (Mt; right) for the baseline (**a**) and scenarios S1 (**b**), S2 (**c**) and S3 (**d**). The baseline values are in absolute terms, while values for the scenarios show net change compared with the baseline. Cropland use is subdivided into EU and non-EU cropland and different crop categories, and end use is subdivided into feed and food. No cropland use is allocated to soybean oil. Fat and protein produced is subdivided by food product (milk, meat, eggs and so on) and by whether it supplies EU diets or the global market for vegetable oil. Flows smaller than 0.1 Mha or Mt are not shown. The segmented circles show the fraction of imports originating from South America (SA, green), North America (NA, orange), Europe outside the EU (E, blue), Southeast Asia (SEA, yellow) and the rest of the world (RoW, grey). The bars show changes in non-EU cropland use per region compared with the baseline.

production need to balance efficient resource use, greenhouse gas emissions and other aspects not covered here (for example, use of chemicals and antibiotics, animal welfare and a range of socio-economic issues).

Use of maize silage rather than grass silage has become common[26] to increase dry matter intake and hence dairy cattle productivity[27]. As maize has a lower protein content than grass, protein-rich concentrates such as soybean meal are needed. Our analysis showed that reduced use of soybean meal in ruminant diets reduced the potential to incorporate maize silage. Thus, the current trend for maize-silage-based livestock diets risks locking the EU into soybean import dependency. Using grass–legume silage instead would increase on-farm protein production[28] and help reduce soybean import dependency.

Halting soybean feed imports reduced demand for cropland in all scenarios—especially in South America. However, demand for cropland in Southeast Asia and Oceania for palm oil production increased by 15% (S1) and 8% (S3) relative to current harvested areas in the regions. In absolute terms, this increased demand was small (0–2 Mha) compared to reduced demand in South America (9–12 Mha). Considering that other studies also indicate that supply of fat is probably more challenging than protein under dietary

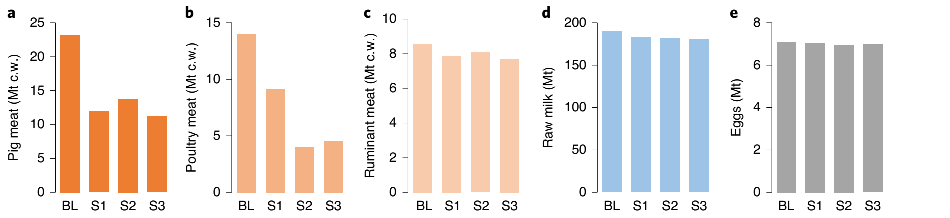

Fig. 4 | EU production of meat, milk and eggs in the baseline and in scenarios S1–S3. a–e, EU production of meat (**a–c**), milk (**d**) and eggs (**e**) in the baseline and in scenarios S1–S3. BL, baseline (2014–2016); S1, feed crops scenario; S2, oil crops scenario; S3, food crops scenario; c.w., carcass weight.

transitions towards less animal-source foods[23], this highlights the importance of ensuring that demand for vegetable oils is sustainably met to avoid relocating impacts between regions, particularly in a situation where vegetable oil fuels are relied on for transitioning from fossil fuels. Therefore, depending on how global demand for fat in relation to protein changes in the future, the S2 (oil) scenario might be preferable to the S3 (food) scenario, although our results indicate a stronger net reduced demand for cropland in the latter scenario. The S1 (feed) scenario gave the weakest reduction in cropland demand in deforestation-prone areas and the strongest increase in palm oil demand. This scenario also shows that there is not enough EU cropland available to produce protein feed for current livestock production if imported soybean is removed, without encroaching on land currently used for other purposes. Studies assessing market effects of reduced EU soybean imports do indeed show a shift in net trade balances towards imports for both cereals and livestock products[16,17], which reveals the risk of pushing production outside EU borders if imports of protein feed are reduced without simultaneously dealing with consumption of livestock products. Thus, while product-based comparisons using LCA show favourable results for local protein feeds[18–21], such solutions do not scale up and may result in relocation of impacts.

Scenarios S1–S3 involved a dietary shift towards more plant-based protein and fat, especially direct consumption of soybean, and reduced consumption of pig and poultry meat. In S1 and S2, only 17–22% of current soybean imports were needed to maintain protein supply to EU diets, revealing the large efficiency gains possible by redirecting feeds with high food value towards human consumption. In S3, soybean imports were eliminated by using EU cropland currently used for feed crops to produce food crops. Current European diets are raising health concerns (for example, obesity and non-communicable diseases), partly related to overconsumption of red and processed meat[29,30]. Consumption of plant-based protein (soybean, pulses and nuts) is, on the other hand, recommended to improve population health[30]; for example, diets rich in soybean can reduce cholesterol levels[31] and endometrial cancer risks[32]. Hence, redirecting soybean from animal to human consumption can reduce cropland demand and improve population health. According to national dietary surveys, the current European diet also greatly exceeds recommended fat and protein intake[33], suggesting that reduced consumption of animal-source food (as in scenarios S1–S3) could meet dietary fat and protein requirements even without additional plant-source food. Reductions in vitamins A and B_{12} and specific amino acids (critically supplied by animal products[34]) were small in all scenarios.

Our analysis highlights the need to apply a food systems approach when investigating large-scale interventions in the food system, such as reduced dependency on soybean imports, which is

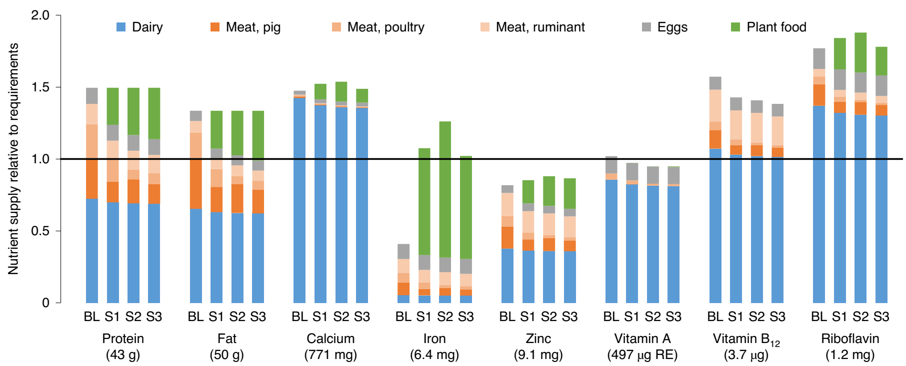

Fig. 5 | Nutrient content of EU-produced animal-source foods and plant-source protein and fat replacements. Nutrient content is normalized to the EU population's weighted average requirement of each nutrient (in brackets). A value of 1 means that the food produced contains 100% of the requirements. For vitamin B_{12}, average requirement data are not available and adequate intake values were used instead. The recommendation for total fat is expressed as a range with a lower and upper bound, where the lower value is used here. Nutrient content refers to edible food produced before any post-farm processing, distribution, retail and household losses, so quantities consumed are lower. BL, baseline (2014–2016); S1, feed crops scenario; S2, oil crops scenario; S3, food crops scenario; RE, retinol equivalents.

highlighted in the EU's Farm to Fork Strategy[13]. Production system analysis (for example, LCA) considering the environmental impact from 1 kg of meat or milk has difficulty capturing interconnections and resource limitations within food systems and may provide poor policy guidance if used in isolation[35]. The model employed here complements such analysis by accounting for limited resources and interconnections based on unnegotiable biophysical relationships. The approach both shows indirect effects on the food system (for example, consequences on oil production when soybean meal is replaced) from the studied intervention (abolishment of soybean imports) and highlights important food systems interlinkages relevant to the outcome (for example, how the use of maize silage drives soybean dependency)—that is, valuable information in the development of policy. To develop policy instruments, additional economic and social effects would also need to be accounted for. Food system models, which fall between simpler product or production system models (for example, LCA) and more complex integrated assessment models, can thus add important knowledge by outlining biophysically feasible future visions[36,37].

We show that abolishing soybean imports for feed can reduce cropland demand in deforestation-prone areas, while maintaining the supply of important nutrients for EU diets. To implement this, progressive EU food system policies simultaneously targeting soybean imports, dietary patterns, and livestock and crop production are needed. These should promote plant-based diets, reverse current declining trends in ruminant production and increasing trends in monogastric production, incentivize use of roughage (clover–grass) that minimizes the need for concentrates in ruminant diets and ensure that vegetable oils can be sustainably sourced, especially under increasing demand from the energy sector.

Methods

Baseline feed use and animal-source food production. To estimate the amount of feed used by the EU livestock sector and production of animal-source food in the baseline (2014–2016), we used country-specific feed rations derived from the Common Agricultural Policy Regionalised Impact (CAPRI) model (version 2.1) together with data on live and slaughtered animals and production of milk and eggs from the FAOSTAT database[38,39], averaged over the period 2014–2016. CAPRI is an economic partial equilibrium model for assessing impacts of EU agricultural policy[40]. The model database is populated with agricultural accounts and trade data mainly sourced from Eurostat and FAOSTAT. The feed rations in CAPRI are based on 11 feed groups, which can be disaggregated to 45 feed items. In this study, some of these were further disaggregated on the basis of data from the EU protein balance sheet[4] (for example, 'Pulses' were disaggregated to 'Field peas', 'Broad beans' and 'Lupins'), resulting in a total of 53 different feeds used in the model. Country-specific average feed rations were considered for seven separate animal categories: (1) dairy cows, (2) other cattle and buffalo (including young animals in dairy herds and animals in beef herds), (3) sheep and goats, (4) breeding pigs, (5) fattening pigs, (6) laying hens and (7) poultry for meat production (broilers, turkeys and other poultry). Fish farming was not included, as it is a small user of soybean compared with terrestrial livestock and no data on farmed fish diets in the EU were available. However, as this sector grows it is important to include it in future analysis.

Inclusion of grass, fodder maize and other crops harvested green (that is, cereals, grasses and leguminous crops, excluding maize, grown on arable land and grazed or harvested either green or as dry hay) was found to be unreliable in the CAPRI feed rations, resulting in unfeasibly high forage intake in many countries and dietary digestible energy content exceeding animal needs. In addition, the CAPRI feed rations resulted in use of fodder maize and other crops harvested green that far exceeded domestic production in some countries, while in other countries the opposite was true. This would require large intra-EU trade flows, which are not likely and not evident in trade statistics[41]. Inclusion of these feeds was therefore adjusted in each country. Inclusion of fodder maize was adjusted on the basis of reported harvests accounting for the fraction of maize silage used for bioenergy production. This fraction was estimated from biogas production in each country according to Eurostat data[42] and the fraction of biogas derived from energy crops[43], assuming a methane yield of 0.298 $Nm^3\,kg^{-1}$ dry matter[44]. Maize is the dominant crop used for biogas production in Europe[43], but other crops are also used. We assumed that maize composes 85% of energy crops used for biogas, on the basis of German data[45]. Inclusion of crops harvested green (other than maize) in rations was adjusted on the basis of reported harvests according to Eurostat[46] assuming that all is used for feed. For permanent grassland, reliable data on harvested quantities are lacking. Inclusion of grass in feed rations was therefore adjusted on the basis of metabolizable energy needs in dairy cattle. For sheep and goats, inclusion of grass was not adjusted. The results from these adjustments compared with the non-adjusted CAPRI rations are presented in Supplementary Table 1. Sensitivity analysis (see Supplementary Information) did however show that these adjustments had a relatively small impact on the main results compared to using the unadjusted CAPRI rations.

Scenario description. To assess the biophysical potential for animal-source food production without soybean imports to the EU and without increasing the land used for feed in the EU, we set up an iterative optimization model and used it to calculate how available feeds after removal of imported soybean should be distributed between different livestock species to maximize production of animal-source proteins to human diets. The starting point was the feeds used in the baseline, which was taken as the feed pool available for livestock in the scenarios. Removing imported soybean from this feed pool resulted in available feeds with less total protein. To maintain the protein/energy ratio in livestock diets, some energy-rich feeds such as cereals were thus also excluded from livestock feed. This freed up EU cropland where these crops are currently grown. We designed three scenarios (S1–S3) of alternative uses of this cropland, all involving use of EU cropland equating to that used for baseline feed production. Indirect effects from replacing crops currently used for other purposes were thereby avoided. All scenarios were designed to supply the baseline amount of edible protein and fat to EU diets and a sufficient amount of vegetable oil to global markets to compensate for reduced production of soybean oil (a consequence of reduced soybean meal production). Soybean for direct human consumption was assumed to be imported to supply baseline levels of edible protein to EU diets and additional palm oil production was assumed to supply additional fat to EU diets and to compensate for reduced associated production of soybean oil. The following sections briefly describes the three scenarios and their rationale.

Feed crops scenario (S1). The need for increased self-sufficiency in feed proteins has repeatedly sparked discussions at the EU level[14,15]. In 2018, the European Parliament adopted a strategy to promote cultivation of protein-rich crops in the EU[47]. This was warranted in part by environmental concerns about soybean production in South America, but also aimed to protect the EU from volatile global markets. Previous research on increasing the environmental sustainability of livestock feed has also shown positive results from substitution of imported soybean meal for EU-grown protein-rich crops[18,20,48]. Scenario S1 therefore assessed the potential for cultivating more leguminous feed crops (soybean, broad bean, peas and lupin) on some of the EU cropland currently used to produce energy-rich feeds. Production was increased proportionally to current EU production volumes of these legume crops. Additional EU soybean produced in the scenario was assumed to be processed into soybean oil and soybean meal, where the meal was used for feed and the oil replaced animal-source fat in EU diets and soybean oil from imported soybean. For the other three crops, the whole seed was assumed to be used for animal feed.

Oil crops scenario (S2). Another proposed substitute for imported soybean meal is by-products from, for example, vegetable oil or ethanol production[18–21]. Scenario S2 therefore assessed the potential of increased rapeseed cultivation on EU cropland made available by reduced use of energy-rich feeds. Rapeseed was selected as it is the highest-yielding oil crop commonly grown in the EU and, like soybean, yields vegetable oil and a protein-rich meal. Rapeseed meal was assumed to be used as animal feed, while rapeseed oil was assumed to replace animal-source fat in EU diets and soybean oil on global markets.

Food crops scenario (S3). Scenarios S1 and S2 still relied on soybean imports for plant-source protein to fill the gap when animal-source food production was reduced. Diets relying more on plant- than animal-based protein sources are widely advocated for health and environmental reasons (for example, ref. [30]). Scenario S3 assessed the potential for cultivating protein-rich plant-source foods on EU cropland currently used to produce energy-rich animal feeds. Cultivation of soybean, broad bean and peas was increased to supply the baseline amount of protein to EU diets. Rapeseed was assumed to be grown on remaining cropland, as described in scenario S2.

Optimization model. In the first step of the iterative optimization model, new feed rations feasible from an animal production perspective (that is, providing the animals with appropriate nutrition) were formulated. The level of detail (53 different feeds) made it possible to set animal-specific constraints on, for example, maximum inclusion rates of different feeds and on essential amino acids. Species-dependent constraints on the nutritional composition of rations were introduced according to equation (1):

$$\sum_{i=1}^{n} a_{p,i,j} \times x_{i,j,k} \times f_{i,j,k} \geq \sum_{i=1}^{n} a_{p,i,j} \times f_{i,j,k} \tag{1}$$

where $f_{i,j,k}$ is the amount of feed i in the baseline feed ration annually fed to each animal j in country k, and $x_{i,j,k}$ is a scaling factor for feed i so that $x_{i,j,k} \times f_{i,j,k}$ gives the annual amount of feed i fed to each animal j in country k in the scenarios. $a_{p,i,j}$ is the value of feed parameter p (for example, metabolizable energy content) of feed i for animal j. Thus, for each animal species, the amount of energy, protein and different amino acids (see Supplementary Table 2) should be equal to or greater than that in current rations. For constraints describing maximum rather than minimum inclusion (for example, total feed intake), a has a negative sign (that is, flipping the inequality constraint). Constraints were thus imposed relative to the baseline feed rations, resulting in new feed rations that are nutritionally equivalent to the baseline feed rations. Soybean meal was limited in feed rations by introducing an equality constraint for the scaling factor x such that soybean meal inclusion in the scenario rations was reduced to a level where only soybean meal of EU origin (currently produced or introduced in the scenario) was used.

New feed rations that were similar to current feed rations, while meeting the constraints, were then found for each animal in each country by minimizing equation (2):

$$\min \sum_{i=1}^{n} \left(b_{i,k} - x_{i,j,k}\right)^2 \quad (2)$$

where $b_{i,k}$ is a weight factor starting at 1 in the first iteration and used to increase or decrease the inclusion of feed i in rations.

Linear programming was used to find the optimal number of each animal category (in terms of supplying edible protein as meat, milk and eggs) in each country, based on the formulated feed rations and available feeds by maximizing equation (3):

$$\max \sum_{j,k=1}^{m,n} n_{j,k} \times p_{j,k} \quad (3)$$

where $n_{j,k}$ is the number of animal j in country k, and $p_{j,k}$ is the amount of edible protein supplied from each animal j in country k. The number of animals in a certain country was constrained either by the availability of a certain feed in that country or the total availability of that feed within the EU, accounting for feeds currently produced and additional production introduced in the different scenarios (that is, soybean meal, peas, broad beans and lupins in S1 and rapeseed meal in S2 and S3). Thus, animal numbers were constrained by feed availability according to feed use in the baseline plus additional feeds introduced in the scenarios. The scope for additional feed production in the EU depended on how much cropland is made available through reduced use of feeds currently grown in the EU. The amount of additional production was manually determined by gradually increasing/decreasing the value until total EU cropland use in each scenario matched that in the baseline.

Feeds that are rarely traded internationally (for example, roughages and bulky by-products such as low-grade vegetables and roots) were constrained to the country level, meaning that use of these feeds in a particular country could not exceed use in the baseline. By-product feeds from processing cereals, oilseeds and sugar crops were constrained on the EU level, meaning that redistribution of these feeds could occur in the scenarios compared with the baseline. To avoid increased livestock agglomeration in the scenarios, cereals and oilseeds used directly for animal feed were constrained on the country level. This ensured that the land base in each country to support its livestock production would not decrease as a consequence of the scenarios. Model sensitivity to this constraint was tested.

The number of animals in each category per country was constrained not to exceed the number of animals in the baseline, to ensure scenarios with a mix of different animals. This meant that livestock production in the scenarios remained fairly similar to the baseline and would thus be able to utilize existing infrastructure. It also avoided dramatic increases in specific animal-source foods, which would require major consumption changes or trade flows to and from the EU. The effects of removing this constraint were also tested in a sensitivity analysis.

As the nutritional composition of different feeds makes them more or less suitable to replace soybean meal in rations, some feeds will limit animal-source food production (that is, be fully utilized), while other feeds will be under-utilized. Weights were therefore put on each feed to increase or decrease its likelihood of being included in the rations, before the next iteration. This was carried out according to equation (4):

$$b_{i,k,t+1} = \begin{Bmatrix} b_{i,k,t} + \left(b_{i,k,t} - b_{\max}\right) \times s_1 & \text{if } \frac{\mathrm{FU}_i}{\mathrm{FA}_i} < 1 - \text{hysteresis} \\ b_{i,k,t} - \left(\frac{1}{b_{\max}} - b_{i,k,t}\right) \times s_2 & \text{if } \frac{\mathrm{FU}_i}{\mathrm{FA}_i} = 1 \\ b_i & \text{if } 1 - \text{hysteresis} > \frac{\mathrm{FU}_i}{\mathrm{FA}_i} < 1 \end{Bmatrix} \quad (4)$$

where FU_i denotes feed use and FA_i denotes feed availability of feed i, either on the EU or country level, as described above. This means that if a certain feed i is fully utilized (FU/FA = 1), the value of $b_{i,k}$ decreases and the goal function described in equation (2) changes to aim for lower inclusion of that feed. If the feed is not fully utilized (FU/FA < 1, with hysteresis set at 0.0001), the value of $b_{i,k}$ increases. The parameters $b_{\max}$, s_1 and s_2 determine the size of increments and decrements in $b_{i,k}$ following each iteration. These parameters were manually determined, to achieve stable behaviour of the optimization model with reasonably fast convergence.

The iterative optimization algorithm described by equations (1)–(4) was iterated until it converged to a solution that represented animal numbers and feed rations that optimally used available feed resources to produce human-edible protein under the defined constraints. The R packages lsei and lpSolve were used to solve the quadratic and linear optimization problems, respectively.

Convergence was assumed when the slope of the goal function (equation (3)) for the 100 latest iterations was close to zero. This was achieved within 360–470 iterations. The approach taken here results in biophysically feasible solutions, but does not necessarily converge to a global optimum. To ensure that the found solution was likely to be close to optimal, feed use in each scenario was compared against feed availability, to ensure that all feeds were close to fully utilized or, if not, that this was due to, for example, low protein/energy ratio or low energy density, making it unfavourable to include that feed in the new feed rations. Constraints were also checked to ensure that there was no oversupply of digestible protein in animal diets compared with the baseline or, if this occurred, that it was explained by another bounding constraint (for example, on a specific amino acid).

Nutritional constraints on animal diets. To ensure feasible feed rations in the scenarios, species-dependent constraints that forced the new feed rations to contain at least the same amounts of energy, protein and specific amino acids as in baseline feed rations were introduced (Supplementary Table 2). Rather than setting constraints in absolute terms, most were set in relation to the baseline feed rations (that is, assuming that livestock production in the scenarios equalled current EU livestock production in terms of productivity and nutritional requirements). Feed rations were also constrained not to exceed the baseline ration's total feed intake on an 'as-fed' basis, to avoid rations relying on unfeasibly high feed intake. Owing to anti-nutritional effects of rapeseed and sunflower seed meal in pig and poultry diets, total inclusion of these feeds was limited.

To calculate the nutritional composition of animal diets, data on nutritional composition of each individual feed were sourced from the feed databases https://feedipedia.org and https://feedtables.com. For feeds not available through those sources (that is, feeds with very limited importance in EU livestock diets), the nutritional composition was estimated on the basis of other similar feeds.

The rations adopted from the CAPRI model and used in this study were defined in terms of feed supplied to animal farms, some of which is lost during storage, handling and feeding. Therefore, to quantify the nutritional characteristics of the animal diets, the fraction of each feed lost before being consumed by animals had to be taken into account. Supplementary Table 3 shows the assumed percentage of feeds lost on farms, based on data from Borreani et al.[49] for fodder and Kertz[50] for other feeds.

Land-use calculations. Use of arable land for EU livestock feed was calculated for all crops (and derivatives) grown with the primary purpose of providing animal feed (that is, where feed is the determining product). No land use was thus attributed to by-product feeds (for example, rapeseed meal, wheat bran, low-grade vegetables and roots, and so on), while feeds such as soybean meal, where protein meal is the main product and oil is a by-product[51], bore the full land use from cultivation. Land use was also calculated for the additional production of plant-source food and vegetable oils introduced as a consequence of each scenario. Our approach thus follows a consequential modelling approach[52] that aims at capturing the land-use consequences of changes.

Trade was accounted for by first estimating the share of each feed component imported from outside the EU, mainly based on imports according to EU protein balance sheets[53–55]. For feeds not covered there (that is, oils and sugar), the imported share was based on their respective EU balance sheets, while also accounting for cases where, for example, vegetable oil is produced within the EU from imported crops. Land use outside the EU was calculated from average yields in exporting countries that account for more than 5% of EU imports according to the EU crop market observatory. After accounting for imports from outside the EU, feed was assumed to be produced within the member state in which it was used. In cases where use for feed exceeded domestic production of a particular crop, the excess was assumed to be imported from other EU countries where production was larger than domestic feed use. In the scenarios, all soybean imports for feed were stopped and reduced use of other feeds was assumed to first affect imports from non-EU countries, then imports from other EU member states and finally domestic production.

Data on yields and total harvested production in EU countries were sourced from Eurostat crop statistics[46], while yield data for non-EU countries were sourced from FAOSTAT data[9]. All yields and imports were averaged over three years (2014–2016) in land-use calculations.

Nutrition calculations. The contribution from animal-source foods, and plant-source foods introduced in the scenarios to the supply of macronutrients and micronutrients to human diets was calculated on the basis of their edible fraction (Supplementary Table 4). The assessment included protein, fat, calcium, iron, zinc, vitamins A, B_{12} and B_2 (riboflavin) and the amino acids lysine, methionine, threonine and tryptophan. These micronutrients were selected owing to their importance for population health and potential deficiency in diets low in animal-source foods[56]. To convert the supply of meat in terms of carcass weight to edible meat, conversion factors from Clune et al.[57] were used. Raw milk from ruminant animals is potentially edible as a whole. However, on the basis of the feed rations used in this study, almost 10% of milk solids produced in the EU are currently used as animal feed (for example, dairy co-products such as whey from cheese manufacture). Thus, we assumed an available edible fraction of 0.9 for raw milk. Likewise, soybean and other pulses are edible as a whole to humans, but to avoid overestimating the potential contribution of plant-source food to dietary nutrition, we applied an edible fraction of 0.8 to soybean, broad beans and peas, based on Wilkinson[58].

After accounting for the edible fraction of each food item, the contribution to macronutrient and micronutrient supply was calculated on the basis of the nutritional composition of each raw food item according to the United States Department of Agriculture FoodData Central database (Supplementary Table 5). As the nutritional composition of meat varies in different parts of the animal, each meat type was subdivided into the commonly used cuts to obtain an average nutrition content for each meat type.

The nutritional contribution from animal-source food and supplementary plant-source food was compared against the EU population's average requirement for each nutrient according to the European Food Safety Authority[59]. As nutritional requirements vary between men and women and between different age groups, demographic data for 2014–2016 according to Eurostat[60] were used to calculate the requirements of the average EU citizen (Supplementary Table 6). The protein requirements are given in relation to body weight. To calculate the EU average protein requirements, reference body weights for different age groups[61] were used with adult weights (that is, 20 years and older) adjusted to match the EU average adult weight of 72.2 kg (ref. [62]).

Feed-use nitrogen load. To assess potential effects of the scenarios on the EU nitrogen balance and associated environmental impacts, the feed-use nitrogen load (FNL), defined as nitrogen present in animal feeds used in a country over the country's total utilized agricultural area, was calculated for each country. FNL acts as a proxy for potential nitrogen surpluses and related environmental problems (that is, in countries with high FNL, manure generation will be large relative to the agricultural area available for spreading). To test the performance of FNL as a proxy for nitrogen surplus, we performed linear regression against the gross nitrogen balance in EU countries according to Eurostat (average 2013–2015). These results are presented and discussed in the Supplementary Information.

Sensitivity analysis. Owing to the uncertainty in several model parameters and choices, we performed a sensitivity analysis. The results are shown in the Supplementary Information, which also contains an in-depth discussion of model limitations and assumptions.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability
Data supporting the findings of this work are available in the Supplementary Data.

Code availability
All computer code needed to run the optimization model and generate data presented here is available from the corresponding author upon request.

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Author contributions

J.O.K., E.R. and P.-A.H. conceptualized the work. J.O.K. led the work, collected data and programmed the main model. A.P. programmed the sub-model calculating the nutritional composition of different food items. All authors contributed to analysing and interpreting results and writing the paper.

Competing interests

The authors declare no competing interests.

Additional information

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Study description	Development of optimization model to find the maximum output of protein from animal source-foods under a number of constraints and seized soybean feed imports.
Research sample	EU-28 (excluding Luxembourg)
Sampling strategy	n/a
Data collection	Agricultural statistics was collected from the EUROSTAT and FAOSTAT databases and nutritional data was collected from the USDA FoodData Central.
Timing and spatial scale	Data was collected for the years 2014-2016.
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The role of livestock in future food systems has been questioned due to their large environmental impacts and inefficient resource use. In this thesis, livestock's potential positive contributions to food system sustainability in terms of using resources otherwise unavailable for food production and managing agricultural landscapes that promote biodiversity and ecosystem services are assessed. It thereby aims to guide food system actors in the challenging task of balancing livestock's positive contributions against the urgent need to reduce their negative impacts.

Johan O. Karlsson received his postgraduate education at the Department of Energy and Technology, Swedish University of Agricultural Sciences (SLU), Uppsala. He holds a Master of Science degree in Environmental and Water Engineering from Uppsala University.

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