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The dairy production system in the north of Sweden under possible future food scenarios

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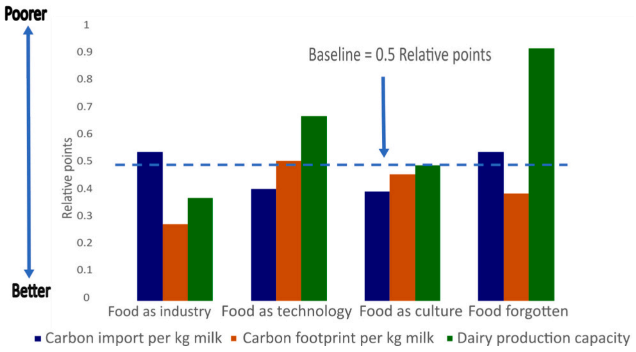
HIGHLIGHTS

- Dairy production plays a vital role in Sweden.
- Impacts of dairy production under different food futures is largely unexplored in Norrland.
- Increasing dairy animals and semi-natural grasslands use has a positive effect on production and carbon import and footprint.
- Biochar production from grass can help dairy production systems to reach net-zero emissions.

GRAPHICAL ABSTRACT



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ABSTRACT

Context: The dairy production system fills an important role by providing nutrient-dense foods in Swedish diets, however, future efforts to improve its sustainability necessitate structural changes.
Objective: We present an innovative study which assesses the effects of these future changes in the dairy system in northern Sweden, the Norrland region, which has a subarctic climate.
Methods: Four scenarios were developed: 1) Food as Industry: Food is a commodity, and its production is an industry that can be invested in to benefit society. 2) Food as Technology: New technologies, such as nutrient density trackers and microbiome mapping, are used for personalized dietary plans. Additionally, novel foods from microbial cultures are produced. 3) Food as Culture: More locally produced food and diverse food products are consumed. 4) Food Forgotten: Land previously used for food and feed is converted to bioenergy production, climate mitigation, and adaptation infrastructure. These scenarios were compared to the baseline i.e. present dairy system for dairy production capacity, carbon flow and carbon footprint.
Results and conclusions: Food as industry resulted in increased dairy production capacity with decreased carbon footprint but increased carbon imports. Food as technology provided decreased dairy production capacity and

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increased carbon footprint but with decreased carbon imports. Food as culture, maintained dairy production capacity with a decreased carbon footprint and carbon imports. Food forgotten resulted in decreased dairy production capacity and increased carbon imports but with decreased carbon footprint. Food as culture benefits all - specifically dairy production capacity, carbon footprint and carbon imports. However, further research is required to explore implications on soil organic carbon stocks over time in Norrland.

Significance: Our study sheds light on the potential impacts of future dairy production in a subarctic climate and aims to help in decision making.

1. Introduction

Dairy production holds a prominent position in Sweden's agricultural sector. Milk, cheese, and butter, are essential sources of nutrients such as protein, calcium, iodine, riboflavin and vitamin B_{12} and play a vital role in Swedish diets, as reflected in the high per capita consumption (Swedish Board of Agriculture, 2022) and Nordic milk and dairy product dietary recommendations of 350–500 ml per day (Blomhoff et al., 2023). Northern Sweden, particularly the Norrland region presents unique agricultural challenges due to its harsh subarctic climate, scattered forest-dominated landscape and short growing season which limit crop cultivation. Despite these challenges, some dairy farmers achieve self-sufficiency in terms of grain crop production mainly by cultivating *Hordeum vulgare* (barley; Landquist and Behaderovic, 2021). Moreover, the long summer days allow grass to accumulate energy-rich carbohydrates and the low early summer temperatures reduce lignification, promoting high-value forage (Krizsan et al., 2021). These conditions favor grassland growth and ley cultivation on arable land, with forage conservation techniques making the region self-sufficient in terms of forage production (Printz, 2023). Consequently, dairy production capacity is relatively high and is supported by several dairy processing plants distributed across Norrland.

Multiple agricultural activities, such as fertilization, machinery operations and crop drying are fossil fuel dependent and contribute to greenhouse gas (GHG) emissions. More specifically, nitrogen (N) fertilization is achieved by manure and/or mineral fertilizers. These mineral N fertilizers are produced outside Sweden, presently using fossil fuels for production of hydrogen, and ammonia based on the Haber-Bosch process (Rafiqul et al., 2005) while other crop nutrients, mainly potassium and phosphorus, are supplied by mining. The cultivation of mixed grass-clover leys, which are common in Norrland, allows for N fixation and thus has a sparing effect on N mineral fertilizer. The application of manure and fertilizers leads to denitrification process in the soil that causes emissions of nitrous oxide (N_2O), a greenhouse gas with a higher global warming potential than carbon dioxide (CO_2) (Peixoto and Petersen, 2023). Furthermore, the digestion of carbohydrates by ruminants results in enteric methane (CH_4) emissions, introducing another potent GHG.

Several strategies have been proposed to reduce the GHG emissions associated with future dairy production systems. These include breeding high-yielding cows (Gerber et al., 2011), increasing crop yields, using fossil-free fertilizers (Suryanto et al., 2021), employing fossil-free fuels (Rahman et al., 2022), reducing enteric CH_4 (Hristov, 2023), and applying biochar to soil in combination with manure (Gross et al., 2022). In Norrland, specific changes have been suggested to enhance the sustainability of the dairy production system. These include increasing the fodder in cow diets, adopting soybean-free diets by utilizing local protein sources, and improving manure handling (Landquist and Behaderovic, 2021). Furthermore, dairy production can, through land use management, either promote carbon sequestration or contribute to carbon loss (Hammar et al., 2022). Thus, any potential changes in Norrland's food production system, including the dairy sector, can have far-reaching implications for dairy production capacity, climate impact and carbon flows associated with the region's agricultural practices.

Few studies have investigated the carbon footprint of dairy under future production scenarios at farm and national level (e.g., Samsonstuen et al., 2024; Sharma et al., 2018; Thivierge et al., 2017). But, to the authors' best knowledge, none have combined dairy production capacity, climate impact and carbon flows for future dairy production systems for a subarctic region. The "MISTRA Food Futures" project (A sustainable and resilient food system | Mistra Food Futures) has explored future food scenarios (Gordon et al., 2022) but the effects of their application to Norrland have not been investigated. Therefore, this study aims to explore how the dairy production systems in Norrland could look like within these different food future scenarios. Specifically, it will scrutinize the projected performance characteristics in terms of dairy production capacity, carbon flows and carbon footprint. The findings will provide valuable insights for decision makers and shed more light on the potential future transformations of the dairy production systems in Norrland.

2. Method

2.1. Description of the scenarios

In the MISTRA food future project, four national scale future food scenarios were designed: Food as industry, Food as technology, Food as culture and Food forgotten (Gordon et al., 2022), a full description is presented in the supplementary materials. We assume that these scenarios are equally applicable to any region in Sweden and have thus developed four dairy production systems for 2045 in Norrland. The study area does not cover all of Norrland but is limited to the catchment area of Norrmejerier, a dairy cooperative operating in Norrland including farms in the counties of Norrbotten, Västerbotten, and parts of Västernorrland and Jämtland.

The dairy production systems under the four scenarios, hereafter referred to by their respective future food scenario names (see Table 1) are assumed to differ based on the e.g., amount of milk produced per cow, cattle populations, reductions in enteric fermentation, proportions of manure used for biochar, yields of crops and grazing management. The semi-natural grasslands are used for grazing by heifers and steers in all scenarios. In all the scenarios the culled cows, bull calves and surplus female calves were sold for beef production. The percentage of milk delivered, sold on farm, fed to calves, and discarded was assumed to be the same as in the baseline (see Table 1). The dairy production system under the four scenarios reflects its possible transformations to improve sustainability in comparison to a baseline dairy production system (today's system – see Section 2.3) in Norrland Sweden.

2.1.1. Food as industry

This dairy scenario presents a sustainable and environmentally friendly approach to increasing dairy production, aligning with the goals of Swedish and EU food policies (Gordon et al., 2022). In the scenario, agriculture and food is seen as an important part of society and as an industry with equal importance for the economy as other industries in Sweden e.g., forestry or steel. The change in dairy production in Norrland is influenced by investment in increased productivity. Arable land use is the same as in the baseline and this determines the cattle population in this scenario. Food as industry has an increase in milk yield per cow compared to the baseline dairy production system, coupled with a decrease in enteric CH_4 production. This decrease in CH_4 is achieved through the implementation of innovative technologies, such as the use of the feed additive 3-nitrooxypropanol (Hristov, 2023) and increase in milk yield per cow by breeding. Additionally, Food as industry assumes higher crop yields per hectare than current levels (Lantmännen, 2019) assuming increased yields without need for higher fertilizer applications due to use of precision agriculture, i.e., improvements in technology in monitoring and managing crop growth for optimization of resources. The production of crops is fossil-free i.e., no fossil-based fertilizers and fuels are used. Furthermore, carbon sequestration is enhanced through the use of biochar derived from all produced manure (Azzi et al., 2024). Food as industry uses less semi-natural grasslands compared to the baseline.

2.1.2. *Food as technology*

This dairy scenario embodies a sustainable and environmentally conscious approach to food production (Gordon et al., 2022). It achieves this by reducing dairy production, introducing innovative food types, and implementing strategic land use changes. These measures highlight the potential for balancing productivity with environmental stewardship in the agricultural sector. We assume that under this scenario, Norrland's transformation in dairy production is spurred by use of land to produce vegetable protein required to make innovative food types i.e., plant-based meat and milk-based analogues. Semi-natural grassland use is the same as in the baseline and this determines the young cattle population and subsequently the entire cattle population. Milk yield per cow is decreased compared to the baseline dairy production system due to increased inclusion of forage in the diet of the animals. In addition, the dairy production system has a reduction in CH_4 emissions due to CH_4 feed additives and an increase in crop yields when compared to the baseline dairy production system, although these changes are less pronounced than in Food as Industry. A portion of the crop production in this scenario utilizes fossil-free inputs, and some of the manure is used for biochar production. Moreover, there is a strategic shift in land use: some arable land is converted back to forests, leading to a reduction in the total arable land area.

2.1.3. *Food as culture*

This scenario describes a sustainable approach to food production that prioritizes small multifunctional farms and is driven by a higher appreciation for rural areas, cultural values, biodiversity and the closer relation between producers and consumers (Gordon et al., 2022). In this dairy scenario, emphasis is placed on increased self-sufficiency and the creation of living and diverse landscapes and rural societies. These changes are facilitated by an increased rural job market coupled with digitalization resulting in more people living in rural and peri-urban areas. Semi-natural grassland use is more than in the baseline and this determines young cattle population and subsequently the entire cattle

Table 1

Description of the dairy production system under different future food scenarios.

		Dairy production system				
	Parameter	Baseline	Food as industry	Food as technology	Food as culture	Food forgotten
Herd description	Annual ECM production per cow, kg	9,953	14,123[*]	6,464[*]	9,345[*]	14,123[*]
	Replacement rate, %	37[††]	36[*]	25[*]	25[*]	36[*]
	Adult cattle herd size	21,409[††]	21,345 cows based on arable land	18,075 cows based on semi-natural grasslands	23,100 cows based on semi-natural grasslands and arable land	1,560 cows based on net zero emissions at farm
	Total number of heifers	15,843[††]	15,095	10,680	13,649	1,103
	Heifer growth rate, g/d	650	715[*]	585[*]	585[*]	715[*]
	Heifer rearing period, d	786	720[**]	866[**]	866[**]	720[**]
Animal diets	Concentrate mixture cows	Commercial concentrate mix	Commercial concentrate mix	By-product-based concentrate mix.	Domesticaly produced ingredients	By-product-based concentrate mix.
	Annual DMI per cow, tonnes	8.30[**]	9.60[**]	6.40[**]	7.50[**]	10.00[**]
	Forage: Concentrate ratio in cow diets	58:42[**]	46:54[**]	75:25[**]	62:37[**]	42:58[**]
	Cow grazing, managed pastures	3 months per year, 5 h/d, 4 kg DMI/d[*]	2 months per year, 5 h/d, 4 kg DMI/d[*]	3 months per year, 12 h/d, 8 kg DMI/d[*]	3 months per year, 18 h/d, 12 kg DMI/d[*]	3 months per year, 5 h/d, 4 kg DMI/d[*]
	Annual Heifer DMI, tonnes	2.50[**]	2.15[**]	2.50[**]	2.50[**]	2.15[**]
	Heifer grazing, semi –natural grasslands	3 months per year, 24 h/d	2 months per year, 24 h/d [*]	4 months per year, 24 h/d [*]	4 months per year, 24 h/d [*]	4 months per year, 24 h/d[*]
	Calf rearing	Commercial calf meal and milk replacer	Commercial calf meal and milk replacer	Commercial calf meal and milk replacer	Commercial calf meal and milk replacer	Commercial calf meal and milk replacer
Crop production	Yield change	–	+50%[*]	+28%[*]	0%[*]	+28%[*]
	Renewable fuel use	0%	100%[*]	50%[*]	50%[*]	100%[*]
	Fossil free fertilizer use	0%	100%[*]	50%[*]	20%[*]	100%[*]
Land use	Arable land use change based on cattle population	28,000 ha	No change [*]	24% decrease (remaining land afforested) [*]	26% increase [*]	92% decrease (remaining land used for grass biochar production) [*]
	Semi-natural grassland change	2,400 ha semi-natural grasslands[†], 540 ha forest pastures[*]	42% decrease in semi-natural grassland use [*]	No change [*]	28% increase in semi-natural grasslands use [*]	92% decrease in semi-natural grassland use [*]
Climate mitigation actions	CH_4 decrease	0%	50%[*]	10%[*]	10%[*]	20%[*]
	Biochar production	0%	100% of manure[*]	20% of manure[*]	20% of manure[*]	100% of manure and grass[*]

ECM: Energy corrected milk; DMI: Dry matter intake.

[†] Source: Landquist and Behaderovic (2021).

[††] Source: Norrmejerier, personal communication 21 September 2023.

[*] Author assumptions.

[**] Norfor calculations (NorFor, 2011).

population. Arable land also increases due to grass-based cattle diets. There is a strong focus on sustainable animals, resulting in breeding for lower average milk production per cow and growth rates than in current production to increase longevity, robustness, and animal health and welfare (Bengtsson et al., 2022). This is accompanied by a decrease in enteric CH_4 emissions using non-synthetic methods such as the incorporation of seaweed into the diet (Hristov, 2023). Crop yield remains unchanged as in the baseline dairy production system and one-fifth of the fertilizer used is fossil-free i.e., the hydrogen for ammonia production is not derived from natural gas but from electrolysis of water using renewable energy. Additionally, some of the manure is used for biochar production, and almost half the fuels used come from renewable sources i.e., biodiesel.

2.1.4. Food forgotten

This dairy scenario describes the change in focus from using land to produce food and feed to using land for climate mitigation. We assume that under this scenario, dairy production is transformed and adapted such that there is an increase in crop yield in line with current trends and that this is achieved using fossil-free fertilizers and fuels. The cattle population decreases to align with net zero emissions resulting in decreased arable land use (feed crops) and semi-natural grassland use compared to the baseline. However, the remaining arable land is used for grass cultivation to produce grass biochar to sequester carbon. There is an intensification of animal production and strong increase in animal productivity compared with the baseline. Milk production per cow and growth rates increase. Furthermore, better nutrition and management combined with the breeding and the use of feed additives result in a decrease of enteric CH_4 emissions. Manure is processed into biochar, resulting in carbon sequestration and partial compensation for the emissions.

2.2. Assumptions

Our assumptions were largely based on MISTRA Future Food scenarios. For example, for Food as industry, we assumed a 50% increase in crop yield and a 42% increase in milk yield (Gordon et al., 2022). However, in some cases, the MISTRA Future Food scenarios provided qualitative descriptions, such as for renewable fuel, fossil fuel and fertilizer use in all future scenarios. For these qualitative descriptions, we developed our own quantitative values (% change from the baseline) based on our judgment. For other assumptions related to animals, such as heifer growth rate, the values presented in this study are related to the nutrition of the heifers. Systems using grazing of heifers on semi-natural grasslands have lower growth rates due to the lower nutritive value of the grass. Grassland-based dairy production also reduces milk yield, which may improve fertility and health in cows, which reduce culling rates and thus decrease the need for replacement heifers. Northern Sweden's agricultural landscape is characterized by high land abandonment (Öhlund et al., 2020). We assumed that land was not a limiting factor in Northern Sweden because of the present abandoned land and underutilized long-term leys. After developing our scenarios, we consulted stakeholders and received confirmation that they were reasonable for the region.

2.3. The baseline dairy production system

The description and the calculations for the baseline dairy production system in catchment area of Norrmejerier (regional level) were based on records at farm level that were submitted to Norrmejerier for the purpose of sustainability reporting, specifically for the year 2022 (Data from Norrmejerier, 2023). Annual deliveries to Norrmejerier were 195,900,000 kg energy corrected milk (ECM) (4.38% milk fat, 3.52% milk protein), after personal communication with Växa (21 March 2024), it was assumed that this corresponds to 92% of the total milk production with the remaining amount being either sold on farm (5%), given to calves (2.5%) or discarded (0.5%). Based on these values annual milk production per cow was set at 9,953 kg ECM (see Table 1) and enteric CH_4 emissions were calculated to 140 kg (NorFor, 2011; Managos et al., 2023). Barley and *Avena sativa* (oats) are used in dairy feeds and the yield for barley and oats cereals stands at 2,700 and 2,600 kg per year respectively (Landquist and Behaderovic, 2021). However, this production is heavily reliant on fossil-based inputs such as fertilizers and fuels. The arable land use is based on the feed intake of the cattle population. In addition, semi-natural grasslands use is based on the population of young animals and forest pasture use is based on the area size by Landquist and Behaderovic (2021).

2.4. Future dairy production capacity

Utilizing the annual quantity of delivered milk and assuming that the dairy system infrastructure was used to its full potential in the baseline, we calculated the future dairy production capacity (FDPC) ratio for Norrmejerier across the various future scenarios. A higher FDPC ratio implies a higher level of production capacity by Norrmejerier. FDPC was calculated as

$$FDPC = future\ production/current\ production \tag{1}$$

Where future production is the quantity of milk produced per year in the future scenarios and current production is the quantity of delivered milk per year in the baseline scenario, all in kg ECM.

2.5. Carbon flows

We used the substance flow analysis (Brunner and Rechberger, 2017) to assess the carbon flows in the study area. The system had five stocks (rectangles): 1) atmosphere, 2) imports, 3) anthroposphere (plants, animal and the topsoil in Norrmejerier's catchment area), 4) exports, and 5) lithosphere (rocks and sediments). It also had ten flows (arrows): 1) CO_2 (the carbon absorbed by plants for photosynthesis), 2) emissions (the carbon discharged from combustion of fossil fuels, enteric fermentation and respiration of animals etc), 3) fuel, 4) fertilizer, 5) feed, 6) seed, 7) plastic, 8) limestone, 9) milk and 10) beef (see Fig. 1).

We analyzed the dairy sector (farms) in Norrland region in Fig. 1 and the activities at the farms are crop production and animal production. For the organic carbon input to soil at the farm, we consider roots, crop leftovers, harvest losses, manure on grassland, and stable manure but not the soil organic carbon (SOC), i.e., the component of soil carbon that remains after the decomposition of organic carbon input to soil by soil organisms (Stockmann et al., 2013; Hoang et al., 2021). The carbon fixed in natural forests and other natural biological processes is excluded.

2.6. Carbon footprint

The carbon footprint model considered the emissions linked from cradle to farm gate as:

$$CF = I + T + P_c + P_{mb}$$

Where CF is carbon footprint of dairy production, I is the GHG emissions for production of inputs used for dairy outside the study area, T is the GHG emissions from transport of inputs to study area, P_c is the GHG emissions from the production of crops in study area and P_{mb} is the GHG emissions from the production of milk and beef in study area all per kg ECM.

Allocation of impacts: We used economic allocation for by-products in feed and biophysical allocation according to IDF (2022) for allocating impacts of milk and beef i.e., between milk and the live weight of sold calves and culled mature females:

$$AF_{milk} = \frac{NE_L * M_{meat}}{NE_L * M_{milk} + NE_G * M_{Meat}}$$

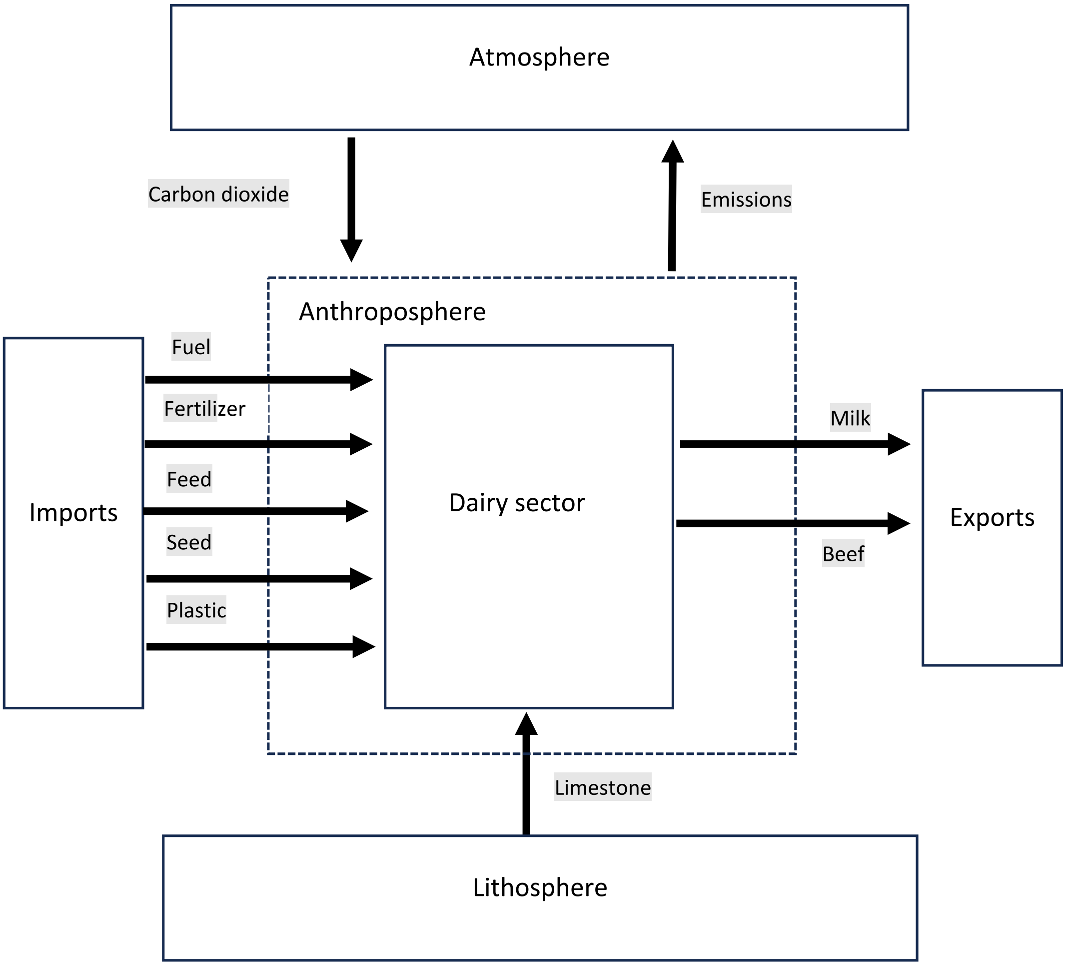

Fig. 1. The conceptual flow of carbon in the Norrmejerier's catchment area.

Where AF_{milk} is the proportion of emissions allocated to milk, M_{meat} is the liveweight of animals sold per year and M_{milk} is the mass of fat and protein corrected milk (FPCM), NE_L is net energy for lactation in MJ/kg FPCM, and NE_G is the net energy for growth in MJ/kg liveweight. The FPCM was standardized according to IDF (2022) with 4% fat and 3.3% protein:

$$FPCM = Production\ (kg/yr)*(0.1226*Fat\% + 0.0776*Protein\% + 0.2534)$$

To convert to FCPM to ECM we used:

$$1\ kg\ ECM = 1.0077\ kg\ FPCM$$

Characterization factors: We used 1 for CO_2, 27.2 for biogenic CH_4, 29.8 for fossil CH_4, and 273 for N_2O (IPCC, 2021).

Functional Unit: We used kg carbon dioxide equivalents per kg ECM (kg CO_2 eq).

Feed intake: The feed intake was based on the output from NorFor model (2011) utilizing the silage, heat treated rapeseed meal and the concentrate mixtures reported by Managos et al. (2023). The diets in the baseline and Food as industry were formulated using a concentrate mix based on ingredients commonly used in cattle diets today. Food technology and Food forgotten utilized a by-products concentrate mix while Food as culture utilized a concentrate mix with ingredients that can be produced domestically in Sweden. The feed composition of the diets of all the animals (cows, heifers and calves) used for baseline and the scenarios are presented in Table 2 for the concentrates and forages.

The sources of greenhouse gases emissions, emission factors and references are present in Table 3 and subsequent section of 2.6.

2.6.1. *On-farm greenhouse gas emissions related to animal production*

On-farm GHG emissions from animals in Norrmejerier's catchment were calculated for enteric fermentation, manure storage and manure on grassland, and energy use for feeding operations. Enteric fermentation CH_4 emissions for lactating dairy cows were based on the results of feed trial (Managos et al., 2023), while for non-lactating dairy cows and heifers on NorFor (2011). Manure storage (CH_4 emissions) and manure on grassland emissions were calculated based on volatile solids using Eq. 10.24, where urinary energy was 0.06 (IPCC, 2019), and digestibility was based on NorFor (2011). We assumed that the manure was stored as slurry and CH_4 emission were calculated based on volatile solids (VS) using emission factors in Table 3.

For manure storage and manure on grassland (direct and indirect N_2O) emissions were based on the N excreted, which was an output of NorFor (2011). Direct and indirect N_2O emissions were based on IPCC (2019) shown in Table 3. Feeding operations energy use emissions (CO_2) were calculated based on the assumption that 26 l of diesel was used per cow place per year (Edström et al., 2005).

2.6.2. *Crop cultivation emissions*

On-farm GHG emissions from crop production were calculated based on the feed intake and feed composition (Table 2), inputs used for crop production i.e. fossil fuel combustion, lime, fertilizer and manure application, and outputs i.e. crop residues. In the scenarios Food as technology and Food as culture, fertilization was based on mineral fertilizers since all the manure was used for biochar production. The greenhouse gas emission factors for fuel, lime and crop residues were calculated based on emission factors shown in Table 3. Crop yield data

Table 2
Feed composition as a percentage of total concentrate feed for baseline and future scenarios in Norrland.

Items	Baseline	Food as industry	Food as technology	Food as culture	Food forgotten
Concentrate use composition					
Triticum aestivum (Wheat), %	6.7	6.5	–	–	–
Wheat middlings, %	–	–	24.9	–	34.0
Wheat bran, %	3.4	3.3	–	–	–
Barley, %	16.2	15.5	18.1	30.9	23.5
Oats, %	–	–	1.8	7.1	2.5
Oat hulls, %	–	–	0.7	–	1.0
Zea mays (Maize), %	21.3	20.7	–	–	–
Vicia faba (Field beans), %	–	–	–	9.5	–
Brassica napus (Rapeseed) by-products, %	37.8	40.3	41.3	32.9	23
Distillers' grains, %	1.1	0.6	7.7	0.9	8.8
Beta vulgaris (Sugar beet) pulp, %	5.5	5.4	1.2	12.4	1.7
Sugar beet molasses, %	2.1	2.0	1.8	2.5	2.5
Minerals, %	2.9	2.8	2.4	3.7	3.1
Rumen protected amino acids, %	0.3	0.2	–	–	–
Vegetable oils, %	2.9	2.7	–	–	–
Total concentrate use (tonnes)	68,000	110,000	31,000	68,000	9,200
Forage use composition					
Silage, %	87	88	74	74	85
Hay, %	3	4	8	3	4
Grassland, %	10	8	18	23	11
Total forage use(tonnes)	150,000	130,000	120,000	160,000	9,700

for crops produced in Norrmejerier's catchment area are shown in the supplementary materials in Table S1 and the quantities of crops are shown in Table S2.

2.6.3. *Biochar production*

Biochar is produced by pyrolysis of organic material, such as manure and grass, and can store carbon for an extended period of time (Azzi et al., 2024; Li and Tasnady, 2023). In this study, biochar is produced from manure in Food as industry and from manure and grass in Food forgotten. In the later scenario, the grass for biochar production was harvested from unfertilized, low yielding grassland (3,000 kg DM per hectare) that remained unused due to reduction in the dairy cattle population. In the same scenario, we assumed that, of the total harvested silage for animal diets, 33% (lower quality) was used for grass derived biochar production. The emission factors for greenhouse gases are shown in Table 3. We assumed that manure derived biochar contains 40% carbon (Struhs et al., 2020), while grass derived biochar contains 70% carbon (Li and Tasnady, 2023).

2.6.4. *Land use related carbon sequestration*

While most studies do not factor in land use effects on carbon when calculating the carbon footprint of dairy, it's crucial to recognize that soil carbon sequestration can play a significant role in reducing the carbon footprint (Henryson et al., 2022). This reduction is possible because the carbon emissions from agricultural activities can be partially compensated for by the transformation of atmospheric CO_2 into plant biomass that is subsequently stored in the soil (Shabir et al., 2023). We assumed that land remaining as grassland sequestrated carbon i.e., 30 kg per hectare for semi-natural grasslands (Karltun et al., 2010) and 140 kg per hectare for cultivated grasslands (Henryson et al., 2022).

2.6.5. *Emissions from dairy inputs from outside Norrmejerier's catchment area*

Inputs used from outside Norrmejerier's catchment area were estimated based on feed intake and feed compositions (see Table 2 and Table S3 of supplementary materials). The inputs included electricity, feedstuffs, diesel, light fuel oil, fertilizers, lime, pesticides, and seed. While most of these inputs were produced in other regions within Sweden, a few, such as fertilizers, were sourced from outside the country. The model accounted for emissions stemming from both the production and transportation of these inputs. The crop production emissions were calculated in the same way for all regionally produced or imported feedstuffs (as described in Section 2.6.2). The calculations were based on crop yield data for crops outside the catchment area, which can be found in Table S1 of the supplementary materials.

Emissions factors for the production and transportation of inputs were estimated based on Ecoinvent 3.9 database (Ecoinvent, 2023) and we assumed emission factors per tonne-km basis for different

Table 3
Source and type of greenhouse emissions, emission factors and references.

Source/Gas	Emission factor	Reference
Manure, CH_4 producing capacity	0.24 m^3 (baseline)	IPCC, 2019
Manure, CH_4 conversion	14% (without CH_4 inhibitors)	
Manure storage, direct N_2O emissions	0.5% of excreted N	
Manure storage, indirect N_2O emissions	1% of N lost as NH3	
Diesel, CO_2 emissions	73 g	Gode et al., 2011
Light fuel oil, CO_2 emissions	74 g	
Limestone applied to soil, CO_2 emissions	0.12 Mg C per Mg $CaCO_3$	IPCC, 2006
Crop residue, mineral fertilizer and manure applied to soil, direct N_2O emissions	1% of N	IPCC, 2019
Crop residue, mineral fertilizer and manure applied to soil, indirect N_2O emissions	1% of N in NH_3 and NO_x 1.1% of leached N	
Fertilizer, NH_3 volatization	11% of N applied	
Manure, NH_3 volatization	21% of N applied	
Soil amendments, N leaching	24% of N applied	
Biochar production from manure, CO_2 emissions	0.07 kg per kg manure	Struh et al., 2020
Biochar production from manure, CH_4 emissions	0.01 kg per kg manure	
Biochar production from grass, CO_2 emissions	0.01 kg per kg grass	

transportation modes. For sea transport, we considered a 10,000 t dead weight container ship. Road transport involved a EURO 5 truck with a load capacity exceeding 20 t, while rail transport assumed an electric locomotive similar to RC4 used in Sweden. Feedstuffs were assumed to be transported by rail from Norrköping to Boden for 1,088 km and by road for 250 km from Boden to the dairy farms (Google, 2023). We assumed that fertilizer, pesticides, and other inputs were transported from Germany to Malmö by ship for a distance of 183 km (Ports.com, 2023) and subsequently, by rail from Malmö to Boden (1,229 km, Google, 2023) and finally by road to the farms as the feedstuffs.

2.7. Sensitivity analysis

Increased milk losses due to the withdrawal of veterinary treatments and a high replacement rate (Växa, personal communication, 21 March 2024), along with high methane emissions, can increase the carbon footprint of milk. We carried out a sensitivity analysis for the baseline and all future scenarios to identify which of these factors influenced the carbon footprint the most. We increased milk losses, replacement rate and methane emissions by 5 percentage points each.

3. Results

3.1. Future dairy production capacity

When comparing the future dairy production systems to the baseline dairy production system, dairy production capacity showed mixed results. Food as industry exhibited a value of 1.4, Food as culture a value of 1, while Food as technology and Food forgotten displayed values of 0.55 and 0.10 respectively.

3.2. Carbon flow

Food forgotten exhibited the largest carbon balance, 320% of the baseline because of carbon sequestered by arable land used for grass production and the carbon locked up in biochar. In contrast, Food as industry had the smallest carbon balance, 82% of the value for the baseline in Table 4. The differences in the carbon balance in Table 4 are due to the variations in emissions of carbon through respiration and enteric fermentation of animals and carbon sequestration due to photosynthesis by crops. The carbon flows to and from the anthroposphere was predominantly connected to the atmosphere. Feed imports contributed 4-19% of the carbon input or inflows to the anthroposphere for the baseline and future scenarios.

3.3. Carbon footprint of dairy production

The footprint without accounting for carbon sequestration presented in Table 5 was between 107–110% of the footprint when carbon sequestration was considered for the baseline and all future scenarios excluding Food forgotten. Methane emissions from enteric fermentation were the primary contributor to the footprint, comprising 54% in the baseline, 46% in Food as industry, 55% in Food as technology, and 54% in Food as culture and 47% in Food forgotten. The differences in the carbon footprint (excluding carbon sequestration) in Table 5 are due to the variations in emissions from crop production and enteric fermentation. For the carbon footprint (including carbon sequestration), the differences are due to variation in emissions from crop production and enteric fermentation, and carbon sequestered. Fossil CH_4 contributed the least to the footprint having 0.9% in the baseline dairy production system, 0.7% in Food as industry, 0.3% in Food as technology, 0.4% in Food as culture and 0.9% in Food forgotten.

Table 4
The carbon flows of the baseline and under future scenarios in kg carbon per kg energy corrected milk.

Parameter	Dairy production system				
	Baseline	Food as industry	Food as technology	Food as culture	Food forgotten
Inflows to anthroposphere					
Imports	0.13	0.15	0.10	0.097	0.15
From Lithosphere	0.0075	0.0053	0.011	0.0093	0.0058
From atmosphere	0.87	0.61	1.3	1.00	3.6
Outflows from anthroposphere					
Exports	0.022	0.021	0.023	0.021	0.021
Emissions to atmosphere	0.48	0.33	0.69	0.49	1.7
Balance					
Anthroposphere	0.51*	0.42*	0.70*	0.59*	2.1*

[*] These carbon balances represent crude values before accounting for long term decomposition.

Table 5
The carbon footprint of the baseline and under future scenarios in kg carbon dioxide equivalents.

Parameter	Dairy production system				
	Baseline	Food as industry	Food as technology	Food as culture	Food forgotten
Excluding carbon sequestration	0.94	0.45	0.98	0.85	0.68
Including carbon sequestration	0.88	0.41	0.90	0.79	-0.004

Table 6
Change in carbon footprint in percentage points for the baseline and all future scenarios after a 5% increase in milk losses, replacement rate and methane emissions.

Parameter	Dairy production system				
	Baseline	Food as industry	Food as technology	Food as culture	Food forgotten
Milk	5.4	5.3	5.5	5.4	5.4
Replacement rate	4.5	2.2	8.1	6.8	0
Methane	1.9	4.4	3.1	2.9	2.9

3.4. Sensitivity analysis

Increasing milk losses by 5 percentage points increased the carbon footprint by an average (for the values shown in Table 6) of 5% of the original values for the baseline and all future scenarios. Similarly, increasing the replacement rate by 5 percentage points increased the carbon footprint by 4%, while increased CH_4 emissions raised the carbon footprint by 3%.

4. Discussion

Our study assessed dairy production systems in a subarctic climate under future food scenarios based on different consumer food values. Few studies have focused on future dairy production in the subarctic regions. A previous study assessing dairy production under different future scenarios in a subarctic climate in Canada by Thivierge et al. (2017) based the scenarios on climate models. The study by Thivierge et al. (2017) showed that under different climate model scenarios, the future carbon footprint decreased due to increased crop yields. Samsonstuen et al. (2024) studied future national dairy production in Norway (part of Norway has subarctic climate) and indicated that the scenario with high production efficiency had a lower carbon footprint per unit milk. To the best of our knowledge, no study involving a region in a subarctic climate compared carbon flows between different scenarios. In addition, no study has compared future food scenarios based on consumers values as in the MISTRA food futures i.e. 1) efficient production, 2) new technologies, such as nutrient density trackers and microbiome mapping and new food production technologies, 3) preference for locally produced food and 4) preference of land use for bioenergy production, climate mitigation, and adaptation infrastructure instead of food and feed production. The findings in our study show that under future food scenarios dairy production varied in terms of dairy production capacity, carbon flows and carbon footprint.

Increasing the milk yields per cow by 40% of the baseline values and using CH_4 inhibitors (decreasing CH_4 by 50%) as demonstrated in Food as industry, decreases the carbon footprint per kg milk by more than half of the value in the baseline and increases the dairy production capacity. However, sustaining such high dairy production capacity requires high concentrate inclusion in the animal diets, specifically more than half of the feed intake on a dry matter basis (approximately 54%). This comes at the cost of larger carbon imports per unit milk and decreased carbon balance in Norrland and this is in agreement with Wall et al. (2019). The concentrate composition required to sustain this level of dairy production capacity requires high dry matter use efficiency (1.47 kg ECM/DMI; Table 1). This necessitates the use of feedstuffs less commonly cultivated in Sweden, such as grain maize, or imported feedstuffs such as rumen protected amino acids and fatty acids distillates from palm oil. The use of these feedstuffs raises a concern about feed-food competition, in Food as industry, approximately 21% of used ingredients could be considered human-edible (Table 2; Wilkinson, 2011). Additionally, increased use of imported feedstuffs also raises another concern i.e., increased vulnerability of dairy production to feed price shocks. Considering Sweden's high lactose tolerance and that it has one of the highest per capita consumptions of non-fermented dairy products (Vuorisalo et al., 2012), increasing dairy production capacity, as seen in Food as Industry, is essential. Surplus milk can be processed into powdered milk or long maturing dairy products, which serve as a strategic reserve for use during years with production deficits.

Leveraging ruminants' ability to convert byproducts of our food system and cellulose-rich biomass to dairy products by the high forage inclusion in animal diets (75% on dry matter basis) as demonstrated in Food as technology, results in a 13% increase in CH_4 emissions per kg milk. The high fiber and low starch content in these diets are responsible for the increases in CH_4 emissions (Nielsen et al., 2013). The increased grazing of semi-natural grasslands by replacement animals results in slower growth rates and longer rearing periods also resulting in increased CH_4 emissions from non-lactating animals. Furthermore, forage-based animal diets supplemented with by-products result in low dry matter use efficiency (1.00 kg ECM/DM intake; Table 1). However, these diets exhibit low feed-food competition, as only 9% of used ingredients are considered as human-edible (Table 2; Wilkinson, 2011), in Food as technology. This comes at the expense of the dairy production capacity as milk yield per cow decreases due to matching the cow's nutritional requirements to the available nutrients in the high fiber diets and also a decreased cattle population. A low dairy production capacity in Norrland might compromise the economic sustainability of the sector, including potential closures of some dairy processing plants due to underutilization, especially given that it is a highly capital-intensive business. High CH_4 emissions do not align well with Swedish climate neutral targets.

Utilization of locally available resources, such as locally produced grains and increasing the cattle population as demonstrated in Food as culture, increases self-reliance in terms of feed production, achieves comparable levels of dairy production capacity, increase the carbon balance and also lowers carbon imports per kg milk compared to the baseline. Even with a moderate decrease of milk yield per cow, coupled with forage-based diets (62% on dry matter basis) and the use of locally produced feeds, dairy production capacity remains comparable to the baseline. The impact of the increase in CH_4 emissions on the carbon footprint per kg milk by grazing of semi-natural grasslands by replacement animals and associated slower growth rates is overshadowed by the inclusion of locally produced concentrate in the diet (Food as culture had a 5% decrease in carbon footprint compared to the baseline). This highlights that moderate forage inclusion in dairy diets and use of grains improves digestibility and increases dry matter use efficiency (1.25 kg ECM/ kg DM intake, as in Food as culture). These factors contribute to the decrease in the carbon footprint per kg milk compared to the baseline. Maintaining dairy production capacity, as seen in Food as Culture and creating diverse landscapes from this practise appears to be an important aspect of the Swedish culture. However, increased feed production on locally available arable land as in Food as culture results in high feed-food competition as approximately 16% of used ingredients could be considered human-edible (Table 2; Wilkinson, 2011).

Intensification of the dairy system such that it achieves carbon neutrality through enteric CH_4 inhibition and carbon sequestration, drastically decreases the herd size and dairy production capacity as demonstrated in Food forgotten. Even with very high milk yield per cow (40% higher) compared to the baseline, dairy production capacity can decrease by as much as 90%. Carbon sequestration through biochar production achieves an impressive 100% reduction in the carbon footprint and a 310% increase in the carbon balance compared to baseline. However, similar to Food as Industry, the high concentrate inclusion in the cattle diets (42% on dry matter basis), comes at the cost of larger carbon imports per unit milk. Intensification of the dairy system using a diet based on byproducts but low in fiber or forage results in a high dry matter use efficiency (1.40 kg ECM/DM intake; Table 1; as seen in Food Forgotten) compared to the low dry matter use efficiency (1.00 kg ECM/ DM intake; Table 1; as seen in Food as technology). This difference highlights the impact of forage inclusion levels, considering that both Food as technology and Food forgotten use the same concentrate mixture. However, more concentrate use raises the feed-food competition concerns once again, because as much as 30% of used ingredients are potentially considered human-edible in Food forgotten (Table 2; Wilkinson, 2011).

Exploring the effects of these scenarios on animal health is challenging. The high milk yields per cow assumed in Food as Industry and Food Forgotten, combined with low forage inclusion in animal diets may result in metabolic problems, fertility issues or udder health issues (Grandl et al., 2019). These pose animal welfare issues and might result in increased animal mortality, high replacement rates and milk losses, ultimately affecting the sustainability of the system.

The dairy systems described in this study result in distinct land use patterns, either through grazing of semi-natural grasslands and managed leys or through the use of arable land both within and outside Norrland. These different land uses have an impact on soil carbon stocks and biodiversity both within the region and beyond. However, Northern Sweden's agricultural landscape is characterized by high land abandonment (Öhlund et al., 2020). Thus, the relation between local feed production, arable land use and biodiversity becomes more complex. Biodiversity is a crucial aspect of dairy production and biodiversity loss needs to be assessed, especially if imported feeds are coming from areas where clearing of forests takes place to make way for crop production (Kyttä et al., 2023; Schader et al., 2014). While the use of crops in dairy production often leads to biodiversity loss, this is not the case in Norrland. Crop production abandonment in favor of long-term leys appears to promote biodiversity. Existing biodiversity assessment methods are not suitable for evaluating this and thus there is a need for localized biodiversity tools specifically tailored for Norrland.

In this study, our focus was primarily on dairy production under the future scenarios. However, we acknowledge that associated changes in crop rotations and the broader food system were not fully captured. As total dairy and beef production shift, there will be corresponding changes in amounts of energy and protein supply, and this will inevitably be accompanied by adjustments in the amount food imported or cultivated in the Norrland region. This will result in additional greenhouse gas (GHG) emissions and could be the focus of future research using a consequential approach.

Given that enteric CH_4 constitutes approximately 50% of milk's carbon footprint (FAO, GDP, 2019), CH_4 mitigation represents a promising strategy. However, feasibility challenges are encountered, especially when it comes to grazing animals or young livestock. A combination of further research and product development is required to address these challenges (Hristov, 2023). The results of our study suggest that solely focusing on CH_4 cannot meaningfully reduce the carbon footprint. Therefore, alternative technologies, such as carbon storage or capture should be considered (Aan den Toorn et al., 2021). In Food forgotten, GHG emissions were completely compensated through carbon sequestration through biochar production, utilizing unused land after the cattle population reduction. Net zero-emissions or carbon neutral dairy production system can thus be achieved depending on land availability. Further research is required to explore other carbon capture and sequestration routes i.e. absorption from manure or biological routes such as algal systems that do not require extensive land use (Yu et al., 2023). Additionally, attention to N is crucial. Optimizing N application rates, favoring ammonium-based fertilizers over nitrate-based ones, incorporating biochar amendments, and using nitrification inhibitors to collectively reduce GHG emissions through N_2O reduction (Pan et al., 2022) needs to be implemented in conjunction with carbon storage and sequestration.

When it comes to carbon flow, we focused on the short-term effects and used organic carbon input to soil rather than soil organic carbon (SOC). The extent to which organic carbon input to soil becomes sequestered depends on whether the soils in Norrland have reached their C saturation point - an upper limit of SOC that is unaffected by decomposition due to mineral protection, based on the soil's physico-chemical characteristics (Guillaume et al., 2022). In the baseline, if the soils have not reached their C saturation point, some if not most of the organic carbon input to soil will be released back into the environment due to decomposition. To gain a more comprehensive understanding, long-term models for carbon flows using SOC can offer a more detailed and site-specific analysis of carbon flow over time.

Regarding the carbon footprint, our study did not specifically focus on peatlands in Norrmejerier's catchment area due to the unavailability of data on area size of peatlands used by the dairy production system. However, given their significant role in carbon emissions (Searchinger et al., 2022), future research could certainly benefit from including them. The results of the sensitivity analysis identified that the carbon footprint was highly sensitive to milk losses. This finding underscores the importance of accurately measuring milk losses, as even small changes can impact the overall carbon footprint. Therefore, it is crucial to collect more reliable and precise data on milk losses to ensure that the models used for calculating the carbon footprint are robust and accurate. Improved milk collection data will help in making more informed decisions and implementing effective strategies to reduce the carbon footprint of dairy production.

Our study neglected economic constraints on dairy production such as labour and input costs. The results of this study are predictions, and therefore, should be interpreted with caution. Our study did not completely capture anticipated technological changes that could take place between now and 2045 and climatic conditions under different climate models e.g. RCP 4.5 and 8.5 (IPCC, 2014) to avoid double counting because we assumed that this was partly captured by Gordon et al. (2022) in the future food scenarios. We also did not factor in the technological changes as not to deviate from the future food scenarios described. Future studies could focus on production under different climate models. Questions still remain for dairy production in the sub-arctic regions: How can genetic selection results in low-CH_4 emitting animals that maintain high productivity under these future scenarios? Can fast growing crops varieties be developed to supply protein and energy to these animals? Future research can focus on these questions.

5. Conclusion

Future food scenarios based on different consumers values have a strong impact on the dairy production system in Norrland. In Food as industry, food is considered a commodity and strong focus in placed in productivity thus changing the dairy system in Norrland to this scenario would result in increased dairy production capacity, with a decreased carbon footprint per unit milk, but with more carbon imports per unit compared to the baseline. Changing to Food as technology, a scenario characterized by food innovation and novel foods, would decrease the carbon imports per unit milk but increase the carbon footprint per unit milk and decrease dairy production capacity. Increased local food production, as seen in Food as culture, leads to changes in the dairy production system that result in decreased carbon footprint and carbon imports per unit milk and similar dairy production capacity compared to the baseline. In Food Forgotten, the dairy sector achieves the net-zero emission target but through drastic decreases in dairy production capacity and increased carbon imports. Increased local food production benefits all i.e. dairy production capacity, carbon footprint and carbon imports. These findings have broader implications, making it possible to assess the role of livestock in the future dairy system and evaluate their productivity, greenhouse gas emissions and contribution to the food system.

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CRediT authorship contribution statement

Stanley Zira: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Markos Managos:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Stina Printz:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Mikaela Lindberg:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Serina Ahlgren:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ulf Sonesson:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

Norrmejerier shared information in this project and did not control the scientific study. The authors declare that they have no conflict of interests that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.104177.

Data availability

No data was used for the research described in the article.

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