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Feed rations in dairy production and their climate footprint

Linking experimental feed trials with life cycle assessment

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Abstract

Dairy production delivers nutrient-dense food but it also constitutes a major source of greenhouse gas (GHG) emissions. Feed formulation plays a central role in shaping both productivity and the climate footprint of dairy systems. This thesis investigated how feed ration formulation can reduce GHG emissions from Swedish high-producing dairy production whilst maintaining productivity. This was addressed across multiple system levels, from the individual animal to the regional food system.

Two feeding trials with dairy cows and heifers evaluated animal performance and enteric methane (CH_4) emissions. Study I compared two pelleted concentrate mixes, formulated with low-carbon-footprint (CF) by-products (BYP) and/or domestically sourced (DOM) ingredients, to a commercially available mix (COM). Both reduced feed-related GHG emissions without compromising feed intake, milk yield, or enteric CH_4 emissions from high-producing (43.3 ± 5.4 kg ECM/d) Swedish Holstein cows. Study II tested a ration designed for forage scarcity, where whole-crop wheat silage was partially incorporated (50:50 DM basis) in grass-clover silage-based diets fed to Holstein and Nordic Red heifers. This substitution did not negatively affect feed intake, growth rate, or enteric CH_4 emissions.

Results from these trials were integrated into a farm-level life cycle assessment (Study III). At the farm level, when compared to COM, BYP decreased total farm-level GHG emissions (-6%) and land use (-3.8%), whilst DOM achieved smaller reductions in farm-level GHG emissions (-2.1% to -2.6%) but increased land use (up to +6.8%). At the regional level (Study IV), scenario modelling of dairy production in northern Sweden illustrated trade-offs among climate footprint, land use, feed self-sufficiency, and milk output.

This thesis demonstrates that feed rations based on low-CF ingredients can reduce GHG emissions from high-yielding Swedish dairy production without compromising animal performance. However, the environmental outcomes depend on ingredient choice and system boundaries, highlighting the need to evaluate feeding strategies at multiple system levels to inform sustainable dairy development.

Keywords: Sustainability, nutrition, roughage, heifer, dairy cow, Sweden

Foderstater i mjölkproduktionen och deras klimatavtryck

Sammanfattning

Mjölkproduktionen tillhandahåller näringsrika livsmedel men är också en betydande källa till växthusgasutsläpp (GHG). Fodret spelar en central roll för såväl produktivitet som klimatavtryck. I denna avhandling undersöktes om sammansättningen av foder påverkar GHG från svensk mjölkproduktion utan att produktiviteten försämras. Frågeställningen behandlades på flera systemnivåer, från den enskilda kon till regional nivå.

I två utfodringsförsök med mjölkkor och kvigor undersöktes mjölkproduktion respektive tillväxt samt metanutsläpp (CH_4) från fodersmältningen. Studie I jämförde två kraftfoderblandningar, sammansatta av råvaror med lågt klimatavtryck (LCF), antingen biprodukter (BYP) och/eller inhemskt producerade råvaror (DOM), med en kommersiellt tillgänglig blandning (COM). Båda LCF-blandningarna minskade foderproduktionsrelaterade GHG utan att påverka foderintag, mjölkavkastning eller CH_4-utsläpp hos högproducerande (43,3 ± 5,4 kg ECM/dag) holstein-kor. Studie II undersökte en foderstat där helsädesensilage av vete delvis ersatte (50:50, torrsubstansbasis) gräs-klöverensilage i foderstater till holstein- och SRB-kvigor, och detta påverkade varken foderintag, tillväxt eller CH_4-utsläpp.

Resultaten från djurstudierna integrerades i en livscykelanalys på gårdsnivå (Studie III): Jämfört med COM minskade BYP den totala klimatpåverkan (-6 %) och markanvändningen (-3,8 %), medan DOM gav mindre minskningar av GHG (-2,1 till -2,6 %), men ökade markanvändningen (upp till +6,8 %). På regional nivå (Studie IV) visade scenariomodellering av mjölkproduktion i norra Sverige avvägningar mellan klimatpåverkan, markanvändning, självförsörjning av foder och mjölkproduktion.

Sammantaget visar avhandlingen att foderstater baserade på råvaror med lågt klimatavtryck kan sänka GHG-utsläppen från svensk mjölkproduktion utan negativ påverkan på djurens prestation. De miljömässiga resultaten beror dock på valet av ingredienser och systemgränser, vilket understryker vikten av att utvärdera utfodringsstrategier på flera systemnivåer för att nå en hållbar utveckling av mjölkproduktionen.

Nyckelord: Hållbarhet, näring, grovfoder, kviga, mjölkko, Sverige

Σιτηρέσια γαλακτοπαραγωγής και το κλιματικό τους αποτύπωμα

Περίληψη

Η γαλακτοπαραγωγή προσφέρει τρόφιμα υψηλής θρεπτικής αξίας, αλλά αποτελεί επίσης σημαντική πηγή εκπομπών αερίων του θερμοκηπίου (GHG). Η διαμόρφωση σιτηρεσίων επηρεάζει καθοριστικά τόσο την παραγωγικότητα όσο και το κλιματικό αποτύπωμα (CF) των γαλακτοκομικών συστημάτων. Η παρούσα διατριβή εξετάζει πώς σιτηρεσια με χαμηλο CF μπορεί να μειώσει τις εκπομπές GHG στη σουηδική γαλακτοπαραγωγή υψηλής απόδοσης, χωρίς μείωση της παραγαγωγικότητας, απο το επίπεδο του ζώου έως το περιφερειακό αγροδιατροφικό σύστημα.

Δύο πειράματα σίτισης αξιολόγησαν την απόδοση και τις εκπομπές εντερικού μεθανίου (CH_4). Στη Μελέτη I, δύο μίγματα συμπυκνωμένων ζωοτροφών, με παραπροϊόντα (BYP) και/ή εγχώρια συστατικά (DOM) χαμηλού CF, συγκρίθηκαν με εμπορικό μίγμα (COM) και μείωσαν τις εκπομπές GHG απο την παραγωγή ζωοτροφών, χωρίς να επηρεάσουν την γαλακτοπαραγωγή ή τις εκπομπές εντερικού CH_4 από αγελάδες Holstein (μεσή γαλακτοπαραγωγικη 43.3 ± 5.38 kg ECM/ημέρα). Στη Μελέτη II, η μερική αντικατάσταση (50% βάσει ξηράς ουσίας) ενσιρώματος γρασιδιού-τριφυλλιου με ενσίρωμα σίτου σε σιτηρέσια δαμαλίδων Holstein και Nordic Red) δεν επηρεασε τον ρυθμό ανάπτυξης ή το CH_4.

Η ενσωμάτωση των αποτελέσματων σε μια ανάλυση κύκλου ζωής (LCA) σε επίπεδο εκμεταλευσης (Μελέτη III) έδειξε ότι το μίγμα BYP μείωσε τις συνολικές εκπομπές GHG (-6%) και τη χρήση γης (LU; -3.8%) έναντι του COM, ενώ μίγμα DOM πέτυχε μικρότερη μείωση εκπομπών GHG (έως -2.6%) αλλά αύξησε τη LU (έως 6.8%). Σε περιφερειακό επίπεδο (Μελέτη IV), η ανάλυση σεναρίων γαλακτοπαραγωγής στη βόρεια Σουηδία ανέδειξε αλληλεπιδράσεις μεταξύ CF, LU, αυτάρκειας σε ζωοτροφές και επιπέδων γαλακτοπαραγωγής.

Συνολικα, σιτηρέσια με συστατικά χαμηλού CF μπορούν να μειώσουν τις εκπομπές GHG χωρίς να υποβαθμίσουν την απόδοση των ζώων. Τα περιβαλλοντικά αποτελέσματα εξαρτώνται από την επιλογή συστατικών και τα όρια του συστήματος, τεκμηριώνοντας την ανάγκη πολυεπίπεδης και πολυδιάστατης αξιολόγησης για την ανάπτυξη βιώσιμης γαλακτοπαραγωγής.

Λέξεις-κλειδιά: βιωσιμότητα, σιτηρέσια, χονδροειδείς τροφές, δαμάλια, γαλακτοπαραγωγές αγελάδες, Σουηδία

Dedication

To my parents, my sister,
my wife and our son,
whom we all look forward to meeting

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. Managos, M., Lindahl, C., Agenäs, S., Sonesson, U., Lindberg, M., (2025). Considering greenhouse gas emissions from feed production in diet formulation for dairy cows as a means of reducing the carbon footprint. animal 19, 101544. https://doi.org/10.1016/j.animal.2025.101544

II. Managos, M., Lindahl, C., Agenäs, S., Lindberg, M. Feed intake, growth rate, and greenhouse gas emissions from pregnant dairy heifers fed either grass-clover silage or a mix of grass-clover silage and whole-crop wheat silage. (manuscript)

III. Managos, M., Lindahl, C., Agenäs, S., Sonesson, U., Lindberg, M. Toward Lower-Carbon Dairy: Life Cycle Assessment of a modelled high-yielding Swedish dairy farm. Journal of Cleaner and Circular Bioeconomy, (submitted)

IV. Zira, S., Managos, M., Printz, S., Lindberg, M., Ahlgren, S., Sonesson, U. (2025). The dairy production system in the north of Sweden under possible future food scenarios. Agricultural Systems, 222, 104177. https://doi.org/10.1016/j.agsy.2024.104177

The contribution of Markos Managos to the papers included in this thesis was as follows:

I. Led the data curation, formal analysis, and visualisation. Contributed to the conceptualisation, methodology, investigation, project administration, and software development. Wrote the first draft and took the main responsibility for review and editing.

II. Led the data curation, formal analysis, and visualisation. Contributed to the conceptualisation, methodology, investigation, project administration, and software development. Wrote the original draft and participated in review and editing.

III. Responsible for the conceptualisation, data curation, formal analysis, investigation, methodology, software, and visualisation. Drafted the original manuscript and contributed to the review and editing.

IV. Shared 1st authorship, shared responsibility for the conceptualisation, data curation, formal analysis, investigation, methodology, software, and visualisation, focusing on the animal production subsystem. Co-wrote the original draft and contributed to the review and editing.

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Abbreviations

3-NOP	3-nitrooxypropanol
aNDFom	Amylase neutral detergent fibre organic matter
BFT	Backfat thickness
BW	Body weight
BYP	By-product-based concentrate mix
CF	Carbon footprint
CH_4	Methane
CO_2	Carbon dioxide
$CO_{2\text{-eq}}$	Carbon dioxide equivalents
COM	Commercial concentrate Mix
CP	Crude protein
DM	Dry matter
DMI	Dry matter intake
DOM	Domestically sourced ingredients mix
ECM	Energy-corrected milk
GHG	Greenhouse gas
GS	Grass-clover silage
HE	Human-edible
iNDF	Indigestible neutral detergent fibre
LCA	Life cycle assessment
LU	Land use
N	Nitrogen
N_2O	Nitrous oxide
NDF	Neutral detergent fibre

OM	Organic matter
OMD	Organic matter digestibility
PMR	Partial mixed ration
RM	Roughage mix
t	Metric tonne

1. Introduction

Climate change is one of the most pressing global challenges of the 21st century, driven by the atmospheric accumulation of greenhouse gases (GHG), such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). International and national commitments, including the Paris Agreement (United Nations 2015), the European Green Deal (European Commission 2019), and the Swedish Climate Act (2017), have set targets to reduce GHG emissions and achieve net zero emissions by combining emission reductions, carbon sequestration, and storage. Agriculture constitutes a significant source of GHG emissions and is therefore targeted in these climate commitments.

In 2022, the agri-food system accounted for 29.7% of the anthropogenic GHG emissions: 48% occurred at the farm gate, 19% from land use (LU) change, and 33% from pre- and post-production. Livestock emissions of CH_4 and N_2O were responsible for about 8% of the global anthropogenic emissions, excluding LU change and off-farm processes (FAO 2024). Hagemann et al. (2012) estimated that milk production up to the farm gate, excluding LU change, accounts for approximately 2.7% of global emissions, rising to about 4.0% when associated dairy beef is considered. These emissions originate from, e.g., animals' digestion, manure management, and soil and crop management. In Sweden, the agricultural sector is explicitly included in the national Climate Act (2017), which aims for net-zero emissions by 2045. Dairy production, primarily its enteric CH_4 and feed-related emissions, is central to achieving these goals.

In many regions, livestock have played a key role in the food system since agriculture's infancy. Historically, herbivores have been kept and bred for their capacity to turn marginal fibrous resources into nutrient-dense food, produce manure for fertilisation, and generate fibre, hides, and traction. Today, cattle occupy a unique position in global food systems, producing an estimated 20% of global meat and 83% of global milk (Mottet et al. 2018). They contribute a highly digestible food that is rich in protein, energy, and essential micronutrients. Global milk production from cattle was estimated at 783 million metric tonnes (t) in 2023, a 60% increase since 2000, with most of the growth occurring in Asia and Africa (FAO 2025a). As the demand for dairy products continues to grow, especially in low- and middleincome regions, their role in the food system must be weighed against their environmental performance.

Balancing dairy's nutritional roles with its environmental footprint illustrates the complexity of dairy sustainability, which can be described as a "wicked problem" (Rittel & Webber 1973). Wicked problems are by definition unsolvable and can thus only be managed. Some wicked problem characteristics that hold particular relevance to dairy sustainability are:

- The solution depends on how the problem is framed and vice versa.
- Stakeholders have radically different world views and frames for understanding the problem.
- The constraints that the problem is subject to, and the resources needed to solve it, change over time.
- The problem is never solved definitively.

Research attention to dairy sustainability has increased rapidly since the early 2000s (Figure 1). This thesis contributes to the field by focusing on the production end of the food system, notably the links between feed formulation, animal productivity, and GHG emissions in Swedish dairy systems.

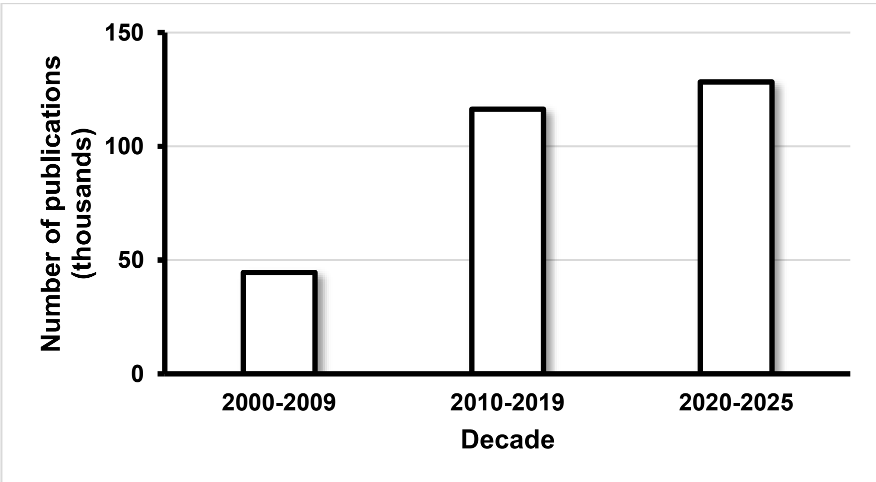

Figure 1. Number of peer-reviewed articles and reviews indexed in Web of Science (search date: 10 September 2025) with keywords related to dairy, cattle, greenhouse gas emissions, enteric methane, and climate change.

2. Background

2.1 Decreasing dairy emissions

Reducing the GHG emissions of dairy production requires a systems-oriented approach that addresses both animal-level and farm-level emissions. Among the available strategies, nutrition and ration formulation are particularly important because they directly influence enteric fermentation, manure composition (Beauchemin et al. 2022), and the upstream emissions associated with feed production. Whilst genetic selection, CH_4-inhibiting additives, and management practices also contribute to GHG mitigation, diet is the most immediate and flexible point.

2.1.1 Dietary composition and GHG emissions

Dry matter intake (DMI) and chemical composition. Ruminants possess a four-compartment stomach (rumen, reticulum, omasum, and abomasum) and the largest compartment, the rumen, hosts a diverse microbial community that ferments feed under anaerobic conditions. Structural carbohydrates such as cellulose and hemicellulose are degraded into short-chain fatty acids (predominantly acetate, propionate, and butyrate), which are absorbed through the rumen epithelium and supply much of the animal's energy. Microbes also convert non-protein N sources (e.g., urea) into microbial protein, which is later digested and absorbed in the lower gastrointestinal tract, providing amino acids (McDonald et al. 2022). This symbiotic fermentation allows ruminants to utilise a variety of feeds (e.g., roughages, cereal and oilseed, and their residues) but it also leads to the production of enteric CH_4 emissions as a by-product.

Dry matter intake (DMI) is a primary driver of total CH_4 emissions (Mills et al. 2003; Yan et al. 2006; Ramin & Huhtanen 2013; Beauchemin et al. 2022). However, high intake levels are essential to maintain both animal productivity and animal satiety, and thus, the goal is to produce more milk/meat for a given DMI level. The chemical composition of the diet directly affects rumen microbial fermentation. Therefore, the relationship between DMI and CH_4 production is modulated by other dietary parameters, including organic matter digestibility (OMD), neutral detergent fibre (NDF), starch, crude protein (CP), and dietary fat (Nielsen et al. 2013; Niu et al. 2021; Donadia et al. 2023). For example, fibre-rich diets promote acetate production, with more metabolic hydrogen available for methanogenesis. However, these diets result in longer rumen retention time, which increases microbial access to organic matter (OM) and favours CH_4 formation (Beauchemin et al. 2022). Higher concentrate inclusion in the diet has the opposite effect due to faster passage rate, whilst higher starch levels promote propionate synthesis, a hydrogen sink that competes with methanogenesis (Janssen 2010). Furthermore, higher starch intake levels increase rumen volatile fatty acids concentrations and decrease rumen pH, affecting methanogens and partially inhibiting them (Van Kessel 1996; Lana et al. 1998).

Lipid supplements may reduce CH_4 production through multiple mechanisms. These include a potent effect on ruminal methanogens and protozoa, whilst in the case of unsaturated fats, they act as minor hydrogen sinks through their biohydrogenation. Lipid supplementation could potentially increase propionate production (Newbold et al. 2015). Lastly, lipids are largely unfermentable, thereby providing direct energy to the animal and replacing OM that could have been fermented by rumen microbes (Beauchemin et al. 2022). The efficacy of lipid supplementation as a CH_4 mitigation strategy depends on several parameters, such as form, fatty acid composition, source, dietary inclusion, degree of saturation, and chemical composition of the ration (Patra 2013). As a result, the chemical composition of the dairy rations directly impacts both animal productivity and the amount of GHGs they emit.

Feed digestibility and ruminal degradation kinetics influence GHG emissions both directly and indirectly. Rations rich in degradable or potentially degradable fractions provide a readily accessible substrate for rumen microbes, which may increase CH_4 production. In contrast, higher passage rates limit rumen retention time and reduce microbial access to the feed, limiting CH_4 production (Beauchemin et al. 2022). Thus, ruminal feed degradability and passage rate are inversely related in their effect on enteric CH_4 emissions. At the whole digestive tract level, higher digestibility can supply the animal with nutrients and reduce the excretion of undigested OM, thereby lowering CH_4 and N_2O emissions from manure storage and application. Moreover, dietary CP levels and ruminal degradation kinetics can affect nitrogen (N) use efficiency, influencing N and the risk of indirect N_2O formation (Montes et al. 2013). Thus, ration formulation can affect GHG emissions beyond enteric CH_4.

2.1.2 Carbon footprint of feed ingredients

In addition to their fermentation in the digestive tract, feed ingredients also contribute to upstream GHG emissions, depending on their origin, cultivation methods, processing, and transport (Henriksson et al. 2014; Mogensen et al. 2014). These emissions vary significantly depending on the ingredient type and its origin (GFLI 2019; RKFS 2021). For instance, oilseeds, oilseed meals, and lipid supplements derived from palm or soy are often linked to high GHG footprints due to the effects of deforestation and LU change associated with oil palm and soybean cropping in tropical regions (Meijaard et al. 2020). The country of origin of each ingredient is also an important parameter. For instance, the carbon footprint (CF) of barley grain can vary depending on national yields and farming practices, ranging from ~360 g carbon dioxide equivalents ($CO_{2\text{-eq}}$)/kg in Sweden to over 1250 g $CO_{2\text{-eq}}$/kg in Portugal (GFLI 2019).

Moreover, high starch rations based on increased grain inclusion may intensify LU pressure and feed-food competition. The production of these grains will result in feed-food competition due to the use of arable land. Additionally, under Swedish conditions, higher grain inclusion can affect crop rotations, reducing the amount of ley grown on the farm, with adverse effects on soil carbon stocks (El Khosht et al. 2025). On a global level, an increased demand for grain can lead to the conversion of permanent pastureland and other marginal land into arable land, resulting in soil carbon loss which further increases GHG emissions (Spawn et al. 2019). These indirect emissions must be considered when evaluating the sustainability of ration formulation and they underscore the importance of integrated GHG assessments that account for both enteric emissions and the climate impact of feed production. Ration formulation presents both an opportunity and a challenge - whilst targeted changes can reduce enteric CH_4, they may inadvertently increase emissions from feed production or shift the burden to other environmental dimensions. Life cycle assessment (LCA) approaches are therefore critical for capturing trade-offs and identifying feeding strategies that reduce the CF of dairy production in a holistic and context-sensitive manner.

2.1.3 Other aspects

Beyond ration formulation and ingredient selection, several additional strategies can influence the environmental performance of dairy systems.

Productivity and emissions intensity. The combination of productivity gains and emission intensity reductions is one of the most widely discussed strategies. Higher yields per animal spread the fixed emissions related to maintenance over a greater output, thus reducing emissions intensity, which is defined as GHG emissions per kilogram of product. This is particularly effective in low- to medium-yielding systems, where gains in milk output result in substantial reductions in GHG intensity (Gerber et al. 2011). However, as yields increase, the marginal gains in emissions efficiency begin to plateau, and other sustainability trade-offs may emerge (Gerber et al. 2011; Sorley et al. 2024). As milk yield rises, cows require more nutrient-dense diets, which in many countries often include imported feed ingredients with a high CF. Additionally, high milk yields may increase the risk of animal health issues (Fleischer et al. 2001) such as mastitis (Jamali et al. 2018), whilst the negative energy balance in early lactation increases the risk of other diseases (Roche et al. 2024). These health issues can affect milk's CF directly due to production losses and decreased feed efficiency, whilst their effect on reproduction, longevity, and herd replacement rate can indirectly increase CF by rearing replacement animals (Clasen et al. 2024).

Ration formulation and feed quality. Ration formulation, the process of designing animal diets to meet specific energy and nutrient requirements, plays a pivotal role in supporting optimised rumen function, animal performance, and minimising emissions (Beauchemin et al. 2022). Feed rations tailored to the animal production level and stage of life allow for more efficient use of the available feed ingredients. High-quality forages, which comprise a significant portion of ruminant diets, provide nutrients and support rumination. For instance, in the context of Swedish dairy production, high-quality grass-clover silage (GS) is a valuable energy and protein source, reducing the reliance on imported protein feeds. Furthermore, ley cultivation has several other agronomic benefits (El Khosht et al. 2025), which are discussed in section 2.3.

Feed additives, breeding, and other aspects. In recent years, interest in CH_4-inhibiting feed additives, such as 3-nitrooxypropanol (3-NOP) (Van Gastelen et al. 2022), seaweed-derived (Angellotti et al. 2025), and nitrates (Van Gastelen et al. 2019) has grown. Although effective in reducing methanogenesis, adopting these additives presents challenges due to dosing method, safety, animal welfare, cost, and potential toxic effects. Moreover, their efficacy could vary depending on diet composition and production systems. Social acceptance regarding the manipulation of animal digestion through feed additives and potential effects on the product's organoleptic characteristics has been investigated to a minimal extent (Hristov et al. 2025). These factors highlight the importance of context-specific evaluation before widespread implementation. Enteric CH_4 emissions can be reduced through genetic selection and breeding. Specifically, selecting dairy cows that are more feed efficient and produce less CH_4 offers a long-term solution. Some examples of other methods to decrease enteric CH_4 are the development of vaccines against methanogens or directly influencing the rumen microbial community through genetic editing techniques (Beauchemin et al. 2022). However, these methods have not been sufficiently successful for widespread implementation and may be subject to restrictions in their use.

Replacement animals and herd longevity. The rearing of replacement heifers also contributes to GHG emissions without contributing to milk output, making herd parameters such as longevity, replacement rate, and calf mortality crucial for farm-level GHG emissions. Extending productive lifespans and improving heifer rearing efficiency can reduce the proportion of unproductive emissions at the herd level (Von Soosten et al. 2020; Clasen et al. 2024).

In summary, these aspects underline that reducing the dairy sector's environmental footprint is a multifaceted challenge that requires integrated strategies that combine productivity gains, ration formulation, feed quality, herd management, and selective adoption of novel technologies.

2.2 Dairy Sustainability Framework

2.2.1 Schools of thought and pillars

Agricultural sustainability can be defined in various ways depending on the priorities and perspectives. Douglass (1984) and later Beede (2013) grouped these perspectives into three schools of thought:

- **Food security**, which prioritises human nutritional needs via ever-improving agricultural productivity and efficiency.
- **Stewardship**, which emphasises maintaining ecological limits and protecting natural resources, for instance, the planetary boundaries framework (Richardson et al. 2023).

- **Society**, which views agriculture as part of a broader social contract (Graddy-Lovelace 2021), that delivers community and cultural benefits (Bojovic & McGregor 2023).

A complementary approach describes sustainability in terms of three interlinked pillars (Khan 1995):

- **Environmental**, for example, GHG emissions, eutrophication, resource depletion, land and water use, and biodiversity impacts.
- **Economic**, including aspects such as economic viability linked to profitability.
- **Social**, including aspects such as fair labour practices, rural vitality, food security, and public acceptance of animal farming.

More recently, animal welfare has been proposed as a fourth pillar, due to the recognition of animal health and well-being as being intrinsic to sustainable food systems (Scherer et al. 2018). These perspectives often overlap and conflict with other aspects of sustainability, illustrating the complexity of assessing and measuring dairy sustainability. For example, feed additives or environmentally certified feed ingredients (e.g., Round Table for Responsible Soy or Roundtable on Sustainable Palm Oil certifications) may reduce GHG emissions but increase costs, thereby improving environmental outcomes but affecting short-term economic sustainability.

2.2.2 Stages of the food system

Consumption. At the consumption end, indicators include per capita dairy intake and its nutritional contribution to the diet. In regions with high food insecurity, dairy products offer a concentrated source of high-quality protein, energy, and essential micronutrients such as vitamin B_{12}, calcium, and iron. Whilst dairy remains nutritionally dense in high-income countries its relative contribution may be lower due to more diverse diets and fortified food options. Nonetheless, dairy products remain important for specific groups, such as children, pregnant women, the elderly, and physically active individuals. Therefore, assessing dairy's role in a sustainable diet requires context-specific evaluation within dietary patterns and demographic groups, rather than relying on single metrics such as protein content or CF. Some studies address this by assigning nutritional indices to foods based on their contribution to dietary adequacy, thereby enabling a more holistic sustainability assessment (Sonesson et al. 2017; Bianchi et al. 2020; Hallström et al. 2022).

Supply chain. From a supply chain perspective, sustainability emphasises circularity, resilience, traceability, and resource efficiency. Circularity, as defined under the circular bioeconomy framework (Van Zanten et al. 2019; Muscat et al. 2021; Van Selm et al. 2022), prioritises using biomass for human food, then for animal feed, and finally for bioenergy or non-food uses. Under this principle, ruminants play a central role by converting by-products and other inedible biomass into food (Röös et al. 2016; van Hal et al. 2019a). Several studies have investigated the effect of by-product inclusion in dairy rations on milk yield and enteric CH4 emissions under Swedish conditions (Pang et al. 2018; Karlsson et al. 2019; Guinguina et al. 2021).

Another important sustainability consideration is the extent to which livestock consume human-edible feeds, often described as feed-food competition (Mottet et al. 2017). Whilst ruminants add value by consuming fibrous forages and by-products, intensification often increases the reliance on cereals and oilseeds that could otherwise be directly consumed by humans. Metrics such as the Human-Edible Feed Conversion Ratio (HeFCR) and Net Food Output (Wilkinson 2011; Ertl et al. 2015, 2016a; Patel et al. 2017) are being increasingly applied to assess these trade-offs, though they may overlook land opportunity costs.

Supply chain sustainability also requires resilience to sudden events. Recent global crises, including the COVID-19 pandemic, the war in Ukraine, and increasingly frequent extreme weather, have highlighted vulnerabilities in international feed supply chains and reinforced the importance of regional self-sufficiency (European Parliament 2018; European Parliamentary Research Service 2023). For instance, in Sweden, the summer drought of 2018 resulted in a significant decrease in crop yields, reduced feed availability, and caused productivity losses and supply chain disruptions. Producing whole-crop cereals silage was a key strategy that allowed Swedish farmers to replace feed for replacement heifers and low-producing cows, reserving high-quality GS for high-producing dairy cows (Statistics Sweden 2018; Spörndly et al. 2019).

Maintaining strategic feed reserves illustrates robustness, whilst ration adjustments demonstrate resilience. Both capacities are essential for sustainable dairy systems under external stress. The length and origin of feed supply chains influence dairy sustainability by reducing deforestation and biodiversity loss in exporting countries, lowering GHG emissions and enhancing resilience to external shocks. Sourcing feed locally can also support regional economies and improve autonomy, though often with the trade-off of higher livestock production costs (European Parliament 2011, 2018; Sasu-Boakye et al. 2014; Deppermann et al. 2018; European Parliamentary Research Service 2023).

These issues are particularly relevant in Northern Sweden. A sub-arctic climate with long winters and a short growing season increases dairy systems' reliance on grasslands and limits the opportunity cost of LU. Furthermore, dairy is central to Northern Sweden's food production, with available pastures providing a practical feed resource for ruminants. These conditions make Norrland a suitable case for scenario analysis, allowing for an assessment of how ration formulation and ingredient sourcing can impact the reliance on imported feed and GHG emissions.

Production end. At the production end, sustainability is shaped by animal productivity, health, and resource use efficiency. Best-practice nutrition and management reduce GHG emissions per kilogram of milk, whilst improvements in manure handling, N use efficiency, soil carbon sequestration, and adopting fossil-free inputs further enhance environmental performance. Crop rotations also affect dairy sustainability. More specifically, ley cultivation can provide agronomic benefits, including a lesser reliance on mineral N fertiliser through biological fixation, improved yields on subsequent crops, enhanced biodiversity, soil structure, and carbon stocks (El Khosht et al. 2025). Ration formulation is particularly important at this stage, as it directly determines animal performance and emissions profiles. The selection of feed ingredients and their chemical composition and integration into crop rotations link farm-level management with broader sustainability outcomes. In Sweden, feed-related emissions are especially relevant, with enteric fermentation (46%) and feed production (41%) contributing almost equally to milk's CF (Henriksson 2014). This underscores the importance of addressing biological and upstream emissions during ration design. Given these multiple and sometimes conflicting dimensions, dairy sustainability must be assessed with system-level methods capable of integrating environmental, economic, and social outcomes. One widely applied tool is LCA, which is introduced in the following section.

2.3 GHG Assessment and LCA

Quantifying the GHG emissions from dairy production is essential to gain a better understanding of the sector's environmental impact and to identify effective mitigation strategies. The GHG emission profile of dairy, when expressed as $CO_{2\text{-eq}}$, is dominated by enteric CH_4, but also includes N_2O and CO_2, originating from manure management, feed production, energy use, and other farm processes (FAO 2025b). To capture these diverse emission sources, researchers and policymakers are growing increasingly reliant on LCA, a standardised framework that evaluates a product's or system's environmental impact across its entire lifespan. In dairy systems, LCAs are frequently conducted using either a cradle-to-farm gate or a cradle-to-grave approach. The former covers processes up to the point of milk leaving the farm, whereas the latter extends to processing, retail, and consumption (IDF 2022).

Accurate LCAs require high-quality input data and clearly defined assumptions. Critical parameters include herd structure and replacement rates, animal productivity, feed intake, and ration composition, crop yields, manure management, and the use of capital goods, energy, and fertilisers (Frischknecht et al. 2007; Flysjö et al. 2011; Guerci et al. 2013; Nguyen et al. 2022; Clasen et al. 2024; Sorley et al. 2024). Furthermore, allocating emissions between co-products such as milk and meat can influence the results. The allocation methods include, but are not limited to, economic (based on market value) or biophysical (based on mass, energy, or protein content) (Ardente & Cellura 2012; Mogensen et al. 2014; Costa et al. 2020; Ineichen et al. 2022). This complexity, especially in dairy sustainability, emphasises the importance of context-specific modelling and transparency in reporting assumptions.

The precision of LCAs can be influenced by how enteric CH_4 is estimated. Many LCA studies rely on tabulated emission factors, but this approach can lead to inaccuracies, especially when applied across diverse diets, breeds, and production systems. For instance, Sorley et al. (2024) addressed this issue by using region-specific CH_4 prediction equations. Henriksson et al. (2014) focused on Swedish dairy systems and adapted manure and feed emission factors to national conditions. The latter study estimated the CF of Swedish milk to be 1.16 kg $CO_{2\text{-eq}}$/kg energy-corrected milk (ECM), with CH_4, N_2O, and CO_2 contributing 50%, 32%, and 18%, respectively. Both studies highlight the significance of feed formulation and animal performance in shaping emission intensity. In Sorley et al. (2024), grazing and mixed systems had lower CFs (1.13-1.24 kg CO_{2-eq}/kg fat and protein corrected milk than fully housed systems (1.52 kg CO_{2-eq}/kg fat and protein corrected milk). Interestingly, the authors also reported that the lowest CF was achieved by a housed herd with very high milk yields and low CF concentrates. This finding illustrates how high productivity can offset certain environmental costs if coupled with sustainable feed choices. Other studies, such as Lovarelli et al. (2024) and O'Brien et al. (2016), further demonstrate that system-level variation can lead to CFs ranging from 0.87 to 1.85 kg CO_{2-eq}/kg fat and protein corrected milk. Such differences are predominantly driven by ration formulation, feed origin, animal-level performance, housing design, heat stress mitigation, and pasture use.

Direct and semi-direct enteric CH_4 measurement methods can provide more robust input data for LCA studies. Respiration Chambers are the gold standard for measuring CH_4 emissions when routinely calibrated and have been shown to achieve approximately 100% gas recovery before and after each experiment. They provide controlled conditions and accurate measurements, however, they are expensive, disruptive to animal behaviour, and limit the sample size (Hammond et al. 2016). The GreenFeed System (C-Lock Inc., Rapid City, South Dakota, USA) is an automated *in situ* spot sampling measurement tool (Hammond et al. 2016; Huhtanen et al. 2019). It consists of a small feeding station that attracts cows with a small portion of concentrate and a sensor that measures exhaled gas concentrations. The system enables on-farm application and possesses the advantage of lower labour and operational costs; however, animals must be trained, can be biased toward more dominant feed-motivated animals, and are more sensitive to diurnal variations. Other techniques, such as the Sulphur Hexafluoride Tracer Technique, sniffers, and laser CH_4 detectors, are less accurate but enable non-invasive, low-cost monitoring (Hammond et al. 2016).

Despite the availability of emission factors and modelling tools, ration-level optimisation is rarely evaluated in terms of both nutritional performance and CF. Integrating empirical feed trial data with system-level modelling allows LCA to link diet, animal physiology, and management practices with the environmental impact of dairy production.

3. Aims & objectives

The overall objective of this thesis was to investigate how feed formulation can reduce GHG emissions in Swedish high-producing dairy systems whilst maintaining productivity. This was addressed across multiple levels of the food system.

Specific objectives:

- Evaluate the impact of by-product and domestically sourced feed ingredients, with a low CF, on dairy cow milk production and enteric CH_4 emissions (Study I).
- Quantify the effects of whole-crop cereal silage on growth performance and CH_4 emissions in pregnant dairy heifers (Study II).
- Model the farm-level GHG emissions and LU implications of the feeding combinations tested in Studies I and II using LCA methodology (Study III).
- Assess the implications of four future scenarios using different management and feeding strategies on dairy production and sustainability in the region of Norrland in Northern Sweden (Study IV).

4. Methodology

A combination of feeding trials with direct measurements of intake, digestibility, and enteric CH_4 emissions, combined with LCA modelling and scenario analysis, was employed to evaluate the environmental and productive implications of alternative feeding strategies. The studies are presented in a hierarchical structure in Figure 2 based on the system level they focus on: animal level assessments (**Studies I and II**), farm level analysis (**Study III**), and regional modelling (**Study IV**).

A comprehensive summary of key details from **Studies I and II** is provided in Table 1. This includes general study information, experimental design, animal characteristics, dietary treatments, data collection procedures, and statistical model. Full descriptions of the materials and methods are provided in each paper and reproduced at the end of this thesis.

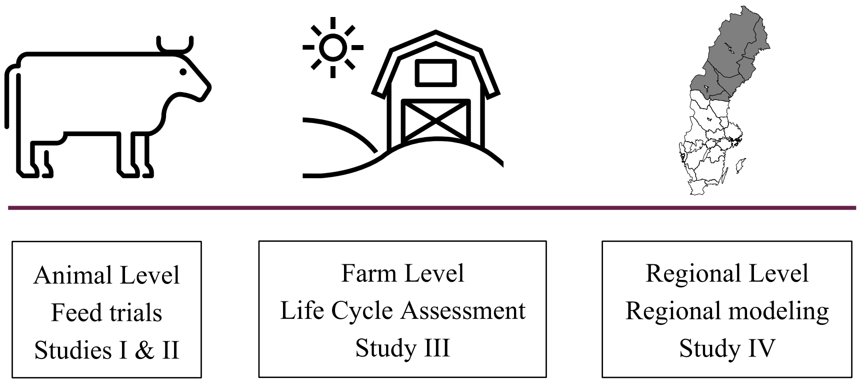

Figure 2. The hierarchical structure of studies is included in the thesis. Map of Sweden adapted from Lappländing, CC BY-SA 2.5, via Wikimedia Commons. (https://creativecommons.org/licenses/by-sa/2.5)

4.1 Studies I and II: Animal-Level Feeding Trials

Studies I and II were feeding trials investigating the effects of feed rations on production parameters. Both studies were conducted at the company Lantmännen's experimental dairy farm "Nötcenter Viken" in Falköping, Sweden (58.1602445934986, 13.59564218533707). A detailed description is presented in Table 1.

The studies focused on different animal categories. **Study I** examined lactating dairy cows to evaluate milk production, feed intake and digestibility, body weight (BW) change, and enteric CH_4 production. Three partial mixed rations (PMRs) were formulated using first-cut GS and either a commercial concentrate mix (COM), a by-product-based concentrate (BYP), or a concentrate composed of Swedish/domestically sourced ingredients (DOM). The silage consisted of timothy (*Phleum pratense* L.), meadow fescue (*Festuca pratensis* L.), and perennial ryegrass (*Lolium perenne* L.) with less than 25% of red clover (*Trifolium pratense* L.) and white clover (*Trifolium repens* L.). The rations were formulated based on the Nordic Feed Evaluation System NorFor® (Volden 2011) in the program IndividRAM (Växa Sweden 2008), using the CF of the ingredients (economic allocation) as a cost function, whilst fulfilling the nutritional requirements for a target milk yield of 45 kg ECM.

Study II examined pregnant dairy heifers and evaluated feed intake and digestibility, growth rate, body composition, and enteric CH_4 production. Two roughage mixes were used, one consisting exclusively of third-cut GS, and the other of a 50:50 DM-basis roughage mix (RM) of GS and whole crop wheat silage harvested at the dough stage. The GS consisted of timothy (*Phleum pratense* L.), meadow fescue (*Festuca pratensis* L.), and perennial ryegrass (*Lolium pratense* L.) with less than 25% of red clover (*Trifolium pratense* L.) and white clover (*Trifolium repens* L.).

Studies I & II both followed a complete blocked design, beginning with a covariate collection period, followed by an adaptation period to the dietary treatments, and a sampling period. Feed intake was recorded daily throughout the experiments using feed mangers on scales (BioControl, CRFI, Rakkestad, Norway). A single GreenFeed system unit (C-Lock Inc., Rapid City, SD, USA) was used to measure enteric CH_4 emissions daily. In **Study I**, animals were milked in a free cow traffic single-station voluntary milking system (310™ system; DeLaval International AB, Tumba, Sweden). In **Study II**, a portable ultrasound unit (LOGIQ™ e Ultrasound, GE HealthCare, Illinois, USA) was used to measure backfat thickness (BFT; Schröder & Staufenbiel 2006). Data from both **Studies I & II** were analysed in R Studio (R Core Team 2022; Posit Team 2024) using linear mixed effect models to evaluate the effects of dietary treatments (Study I: COM, BYP, DOM; Study II: GS, RM) on the response variables.

Table 1. Description of Studies I and II.

		Study I	Study II
General information	Location	Falköping, Sweden	Falköping, Sweden
	Infrastructure	Nötcenter Viken	Nötcenter Viken
	Date	May-June 2022	August-September 2024
Experimental treatment & design	Treatment (abbreviation)	COM, BYP, DOM	GS, RM
	Experimental design	Randomised complete block design	Randomised complete block design
	Blocking Criteria	2 blocks based on parity	11 blocks based on breed and BW
	Adaptation period, weeks	2	1
	Data collection period, weeks	7	4
Animals	Animal category	Lactating dairy cows	Pregnant dairy heifers
	Breed & Number of animals	Swedish Holstein (48)	Swedish Holstein (14), Nordic Red (8)
	Days in milk, d	185 ± 50	-
	Days in pregnancy, months	3.3 ± 1.58	3.9 ± 0.95
	BW, kg	675 ± 54	474 ± 38.5
	Parity	15 primiparous, 33 multiparous	0 (nulliparous)
	Lactation number	2.8 ± 1.0	-
	Age, months	46.3 ± 13.47	18.3 ± 1.16

		Study I	Study II
Feeding	Feeding Strategy	PMR *ad libitum*, up to 6 kg pellets via AMS, sugar beet pulp pellets (Betfor®) from GreenFeed	Roughage *ad libitum*, up to 1.2 kg/d sugar beet pulp pellets (Betfor®) from GreenFeed
Data collected	Methane Emissions	GreenFeed system	GreenFeed system
	Feed Intake	BioControl & GreenFeed	BioControl & GreenFeed
	Feed Quality	Chemical analysis	Chemical analysis
	Digestibility Marker	iNDF, faecal spot sampling	AIA, faecal spot sampling
	Milk yield	Automated recordings (DeLaval)	-
	Milk quality	Mid-infrared spectroscopy	-
	Other Animal Measurements	BW	BW, BFT
Statistical analysis	Model	Linear mixed-effects model with a continuous AR(1) correlation structure.	Linear mixed-effects model with a continuous AR(1) correlation structure.
	Covariates	Milk & ECM yield, DMI, BW, DIM	DMI, BW, BFT, CH_4

Abbreviations: COM = Commercial concentrate mix; BYP = By-products based concentrate mix; DOM = Concentrate mix based on domestically sourced ingredients; GS = Grass-clover silage; RM = Roughage mix; BW = Body weight; PMR = Partial mixed ration; AMS = Automatic milking system; iNDF = indigestible neutral detergent fibre; AIA = Acid insoluble ash; BFT = Backfat thickness; AR(1) = Autoregressive model of order 1; ECM = Energy corrected milk; DMI = Dry matter intake; DIM = Days in milk; OM = Organic matter; CH_4 = Methane.

4.2 Farm and Regional-Level Studies

Studies III and IV assessed the effects of implementing the diet combinations tested in **Studies I and II** at higher system levels (Farm and Region level, respectively).

4.2.1 Study III: Farm-Level LCA

Study III was an attributional LCA, evaluating the GHG emissions and LU of six diet combinations implemented on a simulated Swedish dairy farm. The herd composition was modelled using data provided by the advisory company Växa Sweden (personal communication, 26 February 2024) for dairy herds using an automatic milking system based on the Swedish official milk recording scheme. The farm's annual milk output was standardised at 12,200 kg ECM per cow.

The diets were formulated using the Nordic feed evaluation System NorFor® (Volden 2011) in the program IndividRAM (Växa Sweden 2008). Feed rations for dairy cows consisted of GS, straw, grazed ley, and three pelleted concentrate mixes (COM, BYP, DOM) as described in **Study I**. Replacement heifers' diets consisted of either GS or RM as in **Study II**. This resulted in a total of six dietary combinations.

Annual farm feed requirements were calculated by extrapolating the results of **Studies I and II**, assuming a 305-day lactation period, a 60-day dry period, a 26.2-month age at first calving, and a 34.5% replacement rate. The farm was assumed to be self-sufficient in roughage production (GS, whole-crop barley silage, and part of the straw) with access to both managed and semi-natural grasslands. A five-year conventional crop rotation was applied, and crop yield data were sourced from the Swedish Board of Agriculture (2025).

The LCA was performed in R Studio (R Core Team 2022; Posit Team 2024) and followed the International Dairy Federation Guidelines (IDF 2022) with a cradle-to-farm-gate system boundary. All farm-level inputs, outputs, LU, and GHG flows were quantified. Emissions were reported as total $CO_{2\text{-eq}}$ and individual GHGs, separated into fossil and biogenic sources.

4.2.2 Study IV: Regional Scenario Modelling

Study IV explored how dairy production systems in Northern Sweden could evolve under four different future food scenarios adapted from the "MISTRA Food Futures" research programme (Gordon et al. 2022). The two northernmost regions of Sweden, hereafter referred to as "Norrland," were selected due to the availability of detailed regional data from the local dairy cooperative Norrmejerier and its specific geographic and climatic conditions. The sub-arctic climate with long winters, a short growing season, and reliance on grasslands limits the opportunity cost of LU compared with other Swedish regions. Additionally, dairy is central to regional food production, making Norrland an interesting case for assessing sustainability and resilience under alternative scenarios. The scenarios were compared to the baseline 2022 dairy system (data from Norrmejerier, 2023).

The scenarios included:

- **Food as Industry:** Characterised by high productivity, full adoption of fossil-free inputs, GHG mitigation technologies (e.g., 3-NOP as a rumen methanogenesis inhibitor, biochar as a means of enhanced soil carbon sequestration), and a high inclusion of concentrate in the rations COM (**Study I**). Arable LU remains unchanged compared to the baseline, and is the determining factor for the cattle population, whilst the use of semi-natural grassland decreases.
- **Food as Technology:** Technology-driven changes to the food system and reduced livestock reliance. Dairy herds are smaller, arable land is partially afforested, milk yield per cow decreases, and rations are based on roughages and BYP (**Study I**). Carbon capture, fossil-free inputs, and enteric CH_4-inhibiting additives are implemented at a smaller scale. The area of semi-natural grasslands restricts the cattle population.
- **Food as Culture:** The food system is local and multifunctional, embedded in biodiverse landscapes. Cattle longevity is prioritised, and rations are based on DOM (**Study I**). Cattle populations are defined by the area of semi-natural grasslands and arable land, balancing biodiversity and productivity. Carbon capture, fossil-free inputs, and enteric CH_4-inhibiting additives are implemented at a smaller scale.

- **Food Forgotten:** Land-based climate mitigation is prioritised. Dairy herds are minimal, with net-zero emissions achieved via fossil-free inputs and 3-NOP (as a rumen methanogenesis inhibitor). Freed-up land is used for grass-based biochar production (as a means of soil carbon sequestration). Dairy rations are based on BYP (**Study I**), and most land is repurposed for carbon capture.

The scenarios varied in herd size, milk yield, LU, feeding strategies, and adoption of climate mitigation technologies. A summary of the scenarios is presented in Table 2. Dairy rations and enteric CH_4 emissions were modelled using the Nordic feed evaluation System NorFor® (Volden 2011) in the program IndividRAM (Växa Sweden 2008) and Study I data, which was extrapolated to an annual production scale. For each scenario, an LCA with a cradle-to-farm-gate system boundary was used. Each scenario was compared to the baseline scenario (dairy production in 2022), and the parameters of interest included: i) change in total regional milk output, ii) carbon flows, iii) GHG emissions, iv) LU, and v) agricultural input requirements. This allowed for a systems-level evaluation of the environmental sustainability of each scenario compared to the baseline. Furthermore, the study highlighted trade-offs across potential futures for the region's dairy sector.

Table 2. Summary of dairy production scenarios in Study IV: baseline (BAS) and future scenarios, Food as Industry (IND), Food as Technology (TECH), Food as Culture (CUL), and Food Forgotten (FORG).

	Dairy production scenario				
Parameter	**BAS**	**IND**	**TECH**	**CUL**	**FORG**
Herd description					
ECM (t/cow/yr)	10.0	14.0	6.5	9.3	14.0
Replacement rate (%)	37	36	25	25	36
Adult cattle (× 10^3)	21.4	21.3	18.1	23.1	1.6
Heifers (× 10^3)	15.8	15.1	10.7	13.6	1.1
Rearing period (d)	786	720	866	866	720
Animal diets					
Concentrate mix	COM	COM	BYP	DOM	BYP
DMI (t/cow/yr)	8.3	9.6	6.4	7.5	10.0
Forage (% of DMI)	58	46	75	62	42
Managed grasslands DMI (t/cow/yr)	0.37	0.24	0.73	1.1	0.37
DMI (t/heifer/yr)	2.5	2.15	2.5	2.5	2.15
Access to semi-natural pastures (months/yr)	3	2	4	4	4
Crop production and inputs					
Yield change (% of baseline)	-	50	28	0	28
Renewable fuel (%)	0	100	50	50	100
Fossil-free fertiliser (%)	0	100	50	20	100
LU					
Arable LU† change (% of baseline)		-	24 afforested	26	92 grass-based biochar

Parameter	Dairy production scenario				
	BAS	**IND**	**TECH**	**CUL**	**FORG**
Semi-natural grassland[††] change (% of baseline)		-42	-	28	-92
Climate mitigation					
Enteric CH_4 inhibition (% of baseline)	0	50	10	10	20
Biochar production	0	100% of manure	20% of manure	20% of manure	100% of manure-grass

Abbreviations: ECM = Energy corrected milk; DMI = Dry matter intake; LU = Land use; CH_4 = Methane; COM = Commercial concentrate mix; BYP = By-products based concentrate mix; DOM = Concentrate mix based on domestically sourced ingredients.

[†]Baseline land use: 28,000 ha

[††]Baseline 2400 ha of semi-natural grasslands and 540ha of forest pastures.

5. Results

The results from the animal-level feeding trials (**Studies I and II**) are presented together due to methodological overlap. The findings from the farm-level LCA (**Study III**) and the regional modelling study (**Study IV**) are reported separately. A comprehensive summary of the key findings from the four studies is presented in Tables 3 - 6. Detailed results, including statistical outputs and figures, can be found in each paper and are presented as a compilation at the end of the thesis. Overall, the results demonstrate that strategic selection of feed ingredients can influence intake, nutrient digestibility, productivity, and CH_4 emissions. Noteworthily, the magnitude of differences in animal-level responses (Studies I and II) did not always align with those focusing on higher system levels.

5.1 Studies I and II: Animal-Level Feeding Trials

The results from **Studies I and II** indicate that the tested dietary treatments performed similarly to conventional/control diets regarding key animal-level outcomes, with certain notable differences in nutrient digestibility and feed-related emissions. The results of **Study I** suggest that rations formulated using ingredients with a low CF (BYP and DOM) perform equally with COM in terms of feed intake, enteric CH_4 emissions, and milk production. Similarly, in **Study II**, GS and RM performed equally regarding feed intake, enteric CH_4 emissions, and growth rate among pregnant dairy heifers. Detailed results from **Studies I and II** are presented in Tables 3 and 4.

In **Study I**, feed intake and the estimated net energy for lactation intake did not differ between cows in the COM, BYP, and DOM treatments. The apparent digestibility results varied across treatments. Cows in the BYP groups exhibited lower DM, OM, and amylase neutral detergent fibre organic matter (aNDFom) digestibility compared with the COM treatment. This decrease in digestibility for the BYP groups was also accompanied by a higher intake of aNDFom and indigestible neutral detergent fibre (iNDF) compared with the COM cows. Cows in the DOM group had the highest aNDFom digestibility compared to COM and BYP.

No difference was observed in ECM yield among treatments, whilst animals in the BYP group had a higher milk fat content. Milk yield during the entire experiment was lower for the cows on the BYP treatment compared to those on the COM treatment, whilst the DOM treatment group did not differ from either. Milk urea N values were elevated for both BYP and DOM compared to COM, potentially indicating differences in rumen N efficiency.

Enteric CH_4 production (g/d), yield (g/kg of DMI), and intensity (g/kg ECM) did not differ between treatments. However, the treatments did differ in terms of GHG emissions associated with the feed ingredients' production. Feed primary $CO_{2\text{-eq}}$ production (g/d), yield (g/kg DMI), and intensity (g/kg ECM) were lower for the BYP and DOM treatments compared to the COM.

In **Study II**, no differences were observed in total DMI, sugar beet pulp pellet intake, or roughage intake between heifers fed GS and RM. However, due to differences in the feed chemical composition, the intake of CP was higher for the GS treatment, whereas the intake of starch was higher for the RM treatment. Feed digestibility was higher in the RM group, as indicated by the higher apparent total tract digestibility of DM and OM. Despite these differences, the average daily gain and the change in BFT were similar between treatments. Enteric CH_4 and CO_2 production (g/d) and yield (g/kg DMI) did not differ between treatments. This suggests that the partial replacement of GS with whole-crop cereal silage did not impact enteric gas production in replacement heifers under these conditions.

Table 3. Results from Study I evaluating the effect of concentrate, commercial (COM), by-product-based (BYP), or domestic (DOM), on feed intake, apparent total-tract digestibility, milk production, enteric CH_4 emissions, and the feed carbon footprint of Swedish Holstein dairy cows. The values are presented as estimated marginal means with standard error of the mean (SEM) and a corresponding P-value.

	Treatment				
	COM	**BYP**	**DOM**	**SEM[1]**	**P-value**
DM intake (kg/d)	24.3	24.7	24.2	0.51	0.707
BW (kg)	697	680	688	5.7	0.071
Milk yield (kg/d)	39.6[a]	36.0[b]	38.7[ab]	0.97	0.017
ECM (kg/d)	38.3	38.5	37.3	0.988	0.635
Fat (%)	3.97[b]	4.29[a]	4.01[b]	0.078	0.004
Protein (%)	3.42	3.45	3.36	0.036	0.143
Lactose (%)	4.56	4.62	4.63	0.032	0.208
Milk urea N (mg/100 mL)	12.0[b]	14.2[a]	13.4[a]	0.260	<0.001
Enteric CH_4 (g/d)	387	378	402	17.3	0.500
CH_4/ECM (g/kg)	10.8	9.82	11.6	0.814	0.241
Feed primary $CO_{2\text{-eq}}$ (kg/d)[††]	11.9[a]	9.42[b]	10.2[b]	0.378	<0.001
Feed primary $CO_{2\text{-eq}}$ /ECM (g/kg)[††]	320[a]	254[b]	284[b]	10.7	<0.001
Apparent digestibility DM (%)	66.8[a]	63.3[b]	66.7[a]	0.61	<0.001
Apparent digestibility OM (%)	68.2[a]	64.7[b]	68.2[a]	0.58	<0.001

Abbreviations: DM = Dry matter; BW = Body weight; ECM = Energy corrected milk; N = Nitrogen; CH_4 = Methane; $CO_{2\text{-eq}}$ = Carbon dioxide equivalents; OM = Organic matter.

[1] Greatest SEM value obtained.

[††] Back-transformed from log-transformed values (antilog scale) for interpretability.

[a,b] Values within a row with different superscripts differ significantly at P < 0.05 after adjustment for multiple testing using Tukey's procedure.

Table 4. Results from Study II evaluating the effect of grass-clover silage (GS) or a 50:50 dry matter basis roughage mix (RM) of grass-clover silage and whole crop wheat silage, on feed intake, apparent total-tract digestibility, average daily gain, and enteric CH_4 emissions from pregnant dairy heifers of the Swedish Holstein and the Nordic Red breeds. The values are presented as estimated marginal means with standard error of the mean (SEM) and a corresponding P-value.

	Treatment			
	GS	**RM**	**SEM[1]**	**P-value**
DMI (kg/d)	10.7	10.0	0.43	0.320
ADG (kg/d)	1.48	1.52	0.057	0.627
BFT change (mm)	0.19	0.52	0.470	0.604
Enteric CH_4 (g/d)	215	221	4.4	0.355
Apparent digestibility DM (%)	65.0[b]	68.9[a]	1.01	0.008
Apparent digestibility OM (%)	66.6[b]	70.3[a]	1.10	0.010

Abbreviations: DMI = Dry matter intake; ADG = Average daily gain; BFT = Backfat thickness; CH_4 = Methane; DM = Dry matter; OM = Organic matter.

[1] Greatest SEM value obtained.

[a,b] Values within a row with different superscripts differ significantly at $P < 0.05$ after adjustment for multiple testing using Tukey's procedure.

5.2 Study III: Farm-Level GHG Emissions and LU

Study III assessed the effects of the diet combinations described in **Studies I and II** on farm-level GHG emissions and LU impacts (Table 5). The GHG emissions and LU were reported both as aggregate ($CO_{2\text{-eq}}$, Total LU) and individual gases (CO_2, fossil, and biogenic CH_4, N_2O), as well as disaggregate LU (on-farm, off-farm).

Combining BYP rations for lactating cows and GS rations for dairy heifers resulted in the lowest GHG per kilogram of ECM. Formulating dairy rations with DOM also reduced the GHG intensity relative to COM-GS to a lesser extent. In contrast, changing from GS to RM increased emission intensity across all concentrate mixtures. Despite the increase in GHG emissions associated with RM, combinations of BYP or DOM with RM still resulted in lower GHG emissions than COM-GS. All diet combinations based on BYP and DOM reduced the global warming effect expressed as $CO_{2\text{-eq}}$ despite a minor increase in CH_4 emissions.

The effect of the diet combinations on LU varied depending on the inclusion of off-farm components. Diets based on BYP reduced the overall LU, primarily due to lower off-farm LU, whilst on-farm LU marginally increased. Conversely, diets based on DOM increased both the off-farm and, to a lesser extent, the on-farm LU. Replacement heifer rations based on RM consistently reduced LU across all combinations.

The sensitivity analysis highlighted that the assumptions about soil carbon stock change and the annual ECM yield per cow had the largest impact on the results. Including soil carbon sequestration reduces the GHG intensity by 12.5-16.4%. Lastly, the break-even analysis indicated that these feeding combinations can result in a decrease of GHG intensity if annual milk yield per cow does not decline by more than 820-830 kg ECM for the BYP-based combinations and 286-360 kg ECM for the DOM-based strategy.

Table 5. Results of Study III evaluating the farm-level greenhouse gas emissions, land use, inputs, and outputs of diet combinations based on commercial (COM), by-product-based (BYP), and domestic (DOM) concentrate diets, and grass-clover silage (GS) or a roughage mix (RM) of grass-clover silage and whole crop cereal silage.

	COM		BYP		DOM	
	GS	RM	GS	RM	GS	RM
Total $CO_{2\text{-eq}}$ (× 10^6 kg/y)	1.54	1.56	1.45	1.46	1.50	1.52
CO_2 (× 10^5 kg/y)	3.10	3.13	2.55	2.58	2.64	2.72
CH_4 (× 10^4 kg/y)	3.00	3.00	3.01	3.02	3.16	3.17
N_2O (× 10^3 kg/y)	1.54	1.57	1.39	1.42	1.40	1.44
$CO_{2\text{-eq}}$/ECM (kg/kg)†	1.05	1.06	0.98	0.99	1.02	1.03
Total LU (ha)	275	253	264	243	275	272
On-farm LU (ha)	240	194	247	201	217	189
LU/ECM (m^2/kg)	1.87	1.72	1.80	1.65	1.87	1.85
Farm feed and straw inputs						
Total feed and straw DM (× 10^5 kg/y)	4.64	5.17	3.91	4.47	4.06	5.29
Straw DM (× 10^4 kg/y)[1]	2.10	6.66	0.14	4.70	4.60	9.16
Concentrate DM (× 10^5 kg/y)	4.43	4.50	3.90	4.00	3.60	4.37
Farm outputs						
ECM (× 10^6 kg/y)	1.30	1.30	1.30	1.30	1.30	1.30
LW (× 10^4 kg/y)	3.42	3.42	3.42	3.42	3.42	3.42
Barley grain DM (× 10^5 kg/y)	1.40	0.24	1.13	-	0.45	-

Abbreviations: $CO_{2\text{-eq}}$ = Carbon dioxide equivalents; CO_2 = Carbon dioxide; CH_4 = Methane; N_2O = Nitrous oxide; ECM = Energy-corrected milk; LU = Land use; DM = Dry matter; LW = Live weight.

[1]Barley straw used as bedding material (6.53 × 10^4 kg DM/y) and the remaining as feed.

5.3 Study IV: Regional Dairy Production Under Future Scenarios

Study IV assessed four future dairy production scenarios for Norrland, using 2022 as a baseline. Dairy rations and enteric CH_4 emissions were based on

Study I, whilst broader system characteristics described as four different future scenarios were adapted from Gordon et al. (2022).

The scenarios showed contrasting impacts on the total regional milk production. Food as Industry, characterised by high productivity (14 t ECM/cow/year) and no change in the number of adult cattle compared to the 2022 baseline scenario, increased regional milk production by 40%. Food as Culture maintained the current regional milk production despite the slightly lower productivity per cow (9.3 t/cow/year) through a slight increase among adult cattle. The lower productivity per cow (6.5 t/cow/year) observed in Food as Technology, combined with the lower number of adult cattle, decreased regional milk output by 45% compared to the baseline. Lastly, in Food Forgotten, the drastic decrease in the adult cattle population reduced regional milk production by 90% compared to the baseline, despite the high animal productivity (14 t/cow/year). In terms of carbon balance, Food Forgotten achieved the greatest improvement, with a 320% increase due to large amounts of carbon stored as biochar (Table 2). In contrast, Food as Industry reduced the carbon balance by 17% compared to the baseline. When accounting for carbon sequestration, Food Forgotten resulted in a net-zero CF (100% reduction), whilst Food as Technology showed a 2% increase. A summary of the results is presented in Table 6.

Table 6. Results of Study IV evaluating dairy production capacity, carbon flow balance, and carbon footprint in Norrland, Sweden, under the baseline (BAS), Food as Industry (IND), Food as Technology (TECH), Food as Culture (CUL), and Food Forgotten (FORG) scenarios.

	Dairy production scenario				
Parameter	**BAS**	**IND**	**TECH**	**CUL**	**FORG**
Regional milk production change (%)[1]	-	+40	-45	0	-90
Carbon flow balance	0.51	0.42	0.70	0.59	2.10
Carbon footprint (kg $CO_{2\text{-eq}}$/kg ECM)					
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

Abbreviations: $CO_{2\text{-eq}}$ = Carbon dioxide equivalents; ECM = Energy-corrected milk.

[1]Change in regional milk production in relation to the 2022 baseline scenario.

6. Discussion

This thesis explored the effect of ration formulation on GHG emissions and milk and meat production in high-producing dairy systems, focusing on Swedish conditions. The four included scientific papers enable comparisons across different levels of the food system, placing the results of feed trials into a broader context and highlighting the opportunities and trade-offs in mitigating emissions whilst maintaining productivity.

6.1 Impact of ingredient selection in Dairy Rations

Study I showed that optimising dairy rations with low CF ingredients can maintain high milk yields without increasing enteric CH_4 emissions. As a result, GHG emissions intensity was reduced, enabling lower total GHG emissions without altering herd size or milk deliveries.

6.1.1 Feed intake, Nutrient utilisation, and Milk production

Both BYP and DOM diets resulted in DMI levels comparable to COM, indicating good palatability and no increase in feed requirements. Yield of ECM was similar across all treatments, despite the lower milk yield for the BYP group, which is consistent with previous research on by-product use (Ertl et al. 2016b; Karlsson et al. 2018; Guinguina et al. 2021). This reflects why ECM is a more accurate measure of milk production since it accounts for milk composition and volume. The higher milk fat content in the BYP group, likely linked to the higher aNDFom intake and the generation of lipogenic precursors in the rumen (van Soest 1994; Van Knegsel et al. 2007), compensated for the lower milk volume. As milk payments are often based on the ECM that is delivered, this suggests that BYP and DOM rations can be adopted without negatively affecting farm income from milk deliveries.

Apparent total tract feed digestibility differed among the treatments, with BYP being lower than both COM and DOM. This finding was in line with earlier studies on by-product dairy diets (Karlsson et al. 2018; Guinguina et al. 2021) and was likely caused by BYP's higher iNDF content. Milk protein content and yield did not differ among treatments. The observed MUN levels for COM and DOM were within the recommended ranges (Ishler 2023), whilst BYP only slightly exceeded this range. This difference between COM and BYP could be explained by the slightly higher CP content (+0.6% units) and potential differences in protein degradability (Nousiainen et al. 2004; Lavery et al. 2025). A small reduction in BYP's CP content and/or a decrease in rumen degradability (e.g., rumen-protected amino acids) could enhance protein-use efficiency and limit urinary N losses without compromising production.

6.1.2 Greenhouse gas emissions

The BYP and DOM feeds' CF was lower than that of COM (BYP: 338 g $CO_{2\text{-eq}}$/kg; DOM: 425 g $CO_{2\text{-eq}}$/kg; COM: 525 g $CO_{2\text{-eq}}$/kg). As DMI and the roughage-to-concentrate intake ratios were similar across all treatments, these differences translated into 21% (BYP) and 14% (DOM) lower total feed $CO_{2\text{-eq}}$ emissions, and 21% and 11% lower emission intensity (g $CO_{2\text{-eq}}$/kg ECM), respectively. This was achieved without increases in enteric CH_4 production or intensity, likely due to the similar DMI levels across treatments. Although BYP had a higher aNDFom intake (which could increase CH_4 production), its higher iNDF content and lower OMD likely counterbalanced methanogenesis.

These results demonstrate that upstream feed-related GHG emissions can be reduced without shifting the emissions burden to the animal level. This aligns with the findings of previous studies that reported no significant differences in CH_4 emissions between by-product and cereal-based diets (Pang et al. 2018) or diets in which field beans replaced soybean meal (Cherif et al. 2018; Johnston et al. 2019). Given CH_4's short atmospheric lifetime (Lynch 2019), maintaining or lowering enteric CH_4 provides near-term climate benefits. Thus, combining BYP/DOM rations with CH_4-reducing additives (e.g., *Asparagopsis spp*. T. or 3-NOP) could deliver additional, system-level GHG gains.

6.1.3 Trade-offs in Diet Formulation and Ingredient Choice

Targeting a low feed CF presented nutrient-use and sourcing trade-offs. The lower digestibility with BYP highlighted the need to balance CF reduction with effective nutrient utilisation. Slightly elevated MUN in BYP/DOM suggested greater ruminal protein degradation and thus minor reductions in the dietary CP levels in addition to rumen-protected methionine, lysine, and/or histidine may benefit these diets (Vanhatalo et al. 1999; Huhtanen et al. 2002). Alternatively, including tanniniferous forages/condensed tannins

(Mueller-Harvey et al. 2019) or microwave treatment (Brodie et al. 2019) could improve N efficiency, reduce urinary N, and potentially lower farm-level N_2O emissions. Additionally, the metabolic conversion of ammonia to urea presents an energy cost for the animal, and consequently an opportunity to improve these diets.

Enteric CH_4 is closely tied to DMI (Mills et al. 2003; Yan et al. 2006; Ramin & Huhtanen 2013; Beauchemin et al. 2022) and is influenced by the dietary content of OMD, NDF, fatty acids, and CP (Nielsen et al. 2013; Niu et al. 2021; Donadia et al. 2023). Mitigation via greater propionate production (e.g., higher starch content), added fat, and/or with CH_4-inhibiting additives is possible, but animal health and fibre digestibility must be protected (e.g., avoid sub-acute rumen acidosis with high starch; avoid >5% DM fat depressing fibre digestion). Ultimately, ingredient sourcing matters. Palm/palm kernel-derived fats typically have higher CF and LU risks (GFLI 2019; Meijaard et al. 2020; RKFS 2021), whereas crushed rapeseed in BYP/DOM had a lower CF, was regional, and aligned with EU traceability/sustainability objectives (European Parliamentary Research Service 2023). Thus, any CH_4-oriented interventions should be evaluated in relation to the upstream climate impacts.

6.1.4 Limitations and Research Needs

Enteric CH_4 was measured through a spot sampling technique (GreenFeed system), which is sensitive to animal behaviour and motivation. An accurate estimation of CH_4 production typically requires at least 30 measurements of sufficient duration (>3 minutes; Arthur et al. 2017), which was not consistently achieved by all animals. Challenges in training and motivation, likely influenced by the availability of up to 7 kg/day of concentrate from the automatic milking system, may have lessened the attractiveness of the GreenFeed unit. A threshold of 20 successful visits was set during data analysis to retain statistical power, but this could have increased residual variance in CH_4 estimates (Arthur et al. 2017; Dressler et al. 2023), particularly in the BYP group (fewer animals/visits). Future trials should include pre-assessing the animal motivation to visit the Greenfeed unit, a longer training period, and establish baseline CH_4 values under stable diets. Considering the moderate heritability of CH_4 (Van Breukelen et al. 2023), accounting for animal-level emission profiles may reduce the unexplained variability.

The feasibility of BYP and DOM should be assessed across full lactations, especially during early lactation. Indeed, early lactation represents a critical period of high energy and nutrient demands, metabolic stress, and hormonal shifts (Ingvartsen 2006). Assessing manure emissions and, where relevant, transport/processing of feeds would complete emission profiles for an LCA. By-product availability and composition can vary, and thus flexible inclusion strategies should be tested across lactation stages, roughage qualities, and roughage:concentrate ratios. Another interesting point to consider is that better alignment between roughage and available protein sources (e.g., adjusting N fertilisation and/or harvesting grass-clover leys when high-CP by-products are available) could optimise dietary CP content and reduce the reliance on mineral N fertiliser. Diet formulation is typically cost-driven, and market failures often limit the adoption of sustainable practices; therefore, the economic sustainability of BYP/DOM diets, as well as the farmers' willingness to adopt these diets, should be evaluated (Opdenbosch 2025).

6.1.5 Practical Relevance for Dairy Systems

Pelleted BYP/DOM concentrates were compatible with automatic milking systems and parlours and can be used in PMR or separate-feeding systems. In our trial, high milk production was maintained, whilst feed-production's CF decreased without raising enteric CH_4. This provides a near-term, implementable mitigation measure that does not rely on new regulatory approvals. At the same time, policy instruments such as the EU Deforestation Regulation (European Parliament and Council of the European Union 2023) will increasingly steer imported feed materials, including palm by-products, towards certified low CF supply chains. Together with the increasing demands for traceability and deforestation-free supply chains (European Parliamentary Research Service 2023), prioritising domestic and low CF ingredients such as cereals, field beans, sugar beet pulp, and rapeseed co-products strengthens the climate performance and policy alignment without sacrificing productivity.

For farm-level carbon accounting and advisory work, these results emphasise assessing feed-associated and enteric emissions together, ensuring CH_4-oriented ingredient choices do not shift burdens upstream. Overall, BYP and DOM feeding combinations offered practical options to lower the whole-ration footprint whilst supporting income from milk deliveries under ECM-based payment systems. By aligning nutritional adequacy, environmental performance, and operational feasibility, these findings help to bridge the gap between experimental research and on-farm practice. They provided a foundation for the broader adoption of low CF, locally sourced feeding strategies in commercial dairy systems.

6.2 Whole-Crop Wheat Silage for Heifers

Study II showed that partially replacing (50:50 DM basis) GS with whole-crop wheat silage did not affect feed intake, enteric CH_4 production, and growth rate in pregnant dairy heifers. Overall, whole-crop wheat silage can be integrated into heifer rations without compromising performance or increasing animal-level climate impact.

6.2.1 Feed intake and average daily gain

Total DMI was comparable between diets. Moreover, the DMI per kg BW (GS: 20.7 g/kg BW; RM: 19.1 g/kg BW) was within the 17.4-23.1 g DMI/kg BW range reported for whole-crop cereal silages (Rustas et al. 2009, 2010, 2011; Wallsten et al. 2009, 2010). The slightly lower DMI of the RM group likely reflected the higher NDF content (GS: 493 g/kg DMI; RM: 511 g/kg DMI; Hoffman et al. 2008). The *ad libitum* feeding was consistent with the relatively high ADG observed in both groups (GS: 1.48 kg/d; RM: 1.52 kg/d). Considering the short duration of the experiment (7 weeks) and the fact that the heifers were at 5.7 (± 0.95) months of gestation by the end of the trial, we do not expect any adverse effects of the high ADG (Larson 2007). Additionally, BFT changes were minor, corresponding to minor changes in the fat reserves (0.95-2.60 kg ± 2.35 kg; 1 mm BFT ≈ 5 kg fat, Schröder & Staufenbiel 2006). Together, these results indicated heifer growth (e.g., skeletal/muscular gain) as opposed to adipose gain, thereby supporting the desired body condition.

6.2.2 Enteric CH_4

Enteric CH_4 and CO_2 production did not differ between the GS and RM treatments, aligning with the comparable DMI levels, which is the primary driver of CH_4 production (Mills et al. 2003; Yan et al. 2006; Ramin & Huhtanen 2013; Beauchemin et al. 2022). Although RM increased starch intake compared to GS, there was no effect on enteric CH_4 production. This suggested that the starch content may have been insufficient for a measurable effect. Dietary CP content is marginally negatively correlated with enteric CH_4 production/yield (Yan et al. 2006; Nielsen et al. 2013). Thus, the higher CP intake in the GS group may have counteracted potential reductions in CH_4. Overall, the findings suggested that moderate changes in silage composition alone may not be adequate in altering enteric CH_4 production in pregnant heifers under *ad libitum* feeding conditions.

6.2.3 Methodology and limitations

Whole-crop cereal silages are heterogeneous, posing practical challenges in collecting representative samples and preventing feed sorting by heifers. The chemical heterogeneity between cereal kernels (high in starch) and straw (high in NDF) increases with crop maturity. Additionally, the physical connection between these two fractions weakens as the plant matures, rendering kernels more prone to detachment during harvesting, mixing, or feed-out. As a result, kernels may be disproportionately lost or separated, which either lowers the starch content of the feed or causes a heterogeneous RM where lighter, fibrous components are at the top and the denser kernels settle at the bottom. These processes can create a feed mix that is less homogenous than intended and may differ in composition from pre-harvest or ensiling samples.

6.2.4 Practical relevance and future research

Considering that both GS and RM resulted in comparable levels of DMI, ADG, BFT, and CH_4, the results of Study II suggested that whole-crop wheat silage can be integrated (50% DM basis) into GS diets. This approach offers dietary flexibility, which can be valuable during GS shortages. The lower CP content and higher OMD observed in the RM group could suggest potential reductions in N excretion and downstream manure CH_4/N_2O. Heifers are a significant emissions source in Swedish dairy production (approximately 20% of milk-unit GHG; Henriksson 2014; Clasen et al. 2024). Future work should test CH_4 inhibitors in heifers and evaluate full-lactation carry-over effects on first-lactation performance and fertility. To the best of our knowledge, this was the first study performed under Swedish conditions to estimate the effect of whole-crop cereal silage on heifer enteric CH_4. It provided empirical data to refine CH_4 estimates in dairy LCA models and indicated a meaningful scope to reduce farm-level emissions via optimised heifer feeding.

6.3 Farm-Level GHG emissions

Study III evaluated six dietary combinations pairing COM/BYP/DOM concentrates with GS or RM heifer roughage (from Studies I and II) within a cradle-to-farm-gate LCA. In brief, BYP feeding combinations decreased total GHG emissions and total LU, whereas DOM feeding combinations decreased total GHG emissions but increased LU, and replacing GS with RM in heifer diets increased GHG emissions and reduced LU. These patterns underlined that ration choices must be evaluated on both CF and LU intensity. A further contribution of Study III was the disaggregated reporting of GHG components which improved cross-study comparisons and aligned with frameworks that differentiate gas lifetimes and warming dynamics.

6.3.1 GHG and LU outcomes

Upstream GHG emissions and LU from the feed ingredient production affected both total farm-level GHG emissions and LU. Relative to COM-GS, low CF ingredients (BYP, DOM) reduced total GHG emissions, predominantly by reducing fossil CO_2 and N_2O emissions from ingredient production. A slight increase in enteric CH_4 emissions anticipated for BYP/DOM did not offset the upstream gains, meaning that GHG intensity per kg ECM was reduced. This is consistent with the findings of Sorley et al. (2024), who observed that intensive systems with limited access to pasture can still achieve a low milk CF when the concentrates consist of low-CF ingredients.

The dietary combinations differed in terms of LU intensity. Compared to the baseline diet combination of COM-GS, diets based on BYP increased on-farm LU. This was primarily because of increased roughage intake driven by the lower concentrate digestibility and a greater proportion of the farm-produced grain being retained for on-farm use (COM: 41%, BYP: 56%). However, this was compensated by lower off-farm LU, due to low LU of by-products, resulting in decreased total LU compared to the other diet combinations. The diet combination based on DOM, on the other hand, increased both on-farm and total LU compared to COM-GS, reflecting the reliance on land-demanding domestically produced crops (e.g., field beans) and a larger share of home-grown barley grains retained on-farm for feeding (COM: 41%, DOM: 81%). The LU intensities observed in this study (1.65-1.87 m^2/kg ECM) were in the lower range (1.5-2.2 m^2/kg ECM) of those reported by Henriksson et al (2014) and exceeded values reported for Western European grazing systems (1.23 m^2/kg fat and protein corrected milk; Sorley et al. 2024). Plausible contributors were the medium-low productivity of Västra Götaland (Reumaux et al. 2023) and GS-based rations for adult cattle. More specifically, the dairy rations reported by Sorley et al. (2024) for herds with pasture access had a higher inclusion of maize silage during the indoor period (13% of total feed ration). Maize typically yields more DM per hectare than grass-clover and can therefore lower LU intensity. In Sweden, the higher LU under DOM may be less problematic given the declining national dairy herd (Karlsson et al. 2023) and a food strategy in which land availability is not currently limiting (Regeringskansliet 2025). Furthermore, the use of semi-natural grasslands for rearing heifers added ~0.33 m^2/kg ECM to LU, a value higher than the 0.1-0.2 m^2/kg ECM reported by Henriksson et. al (2014), which increased total LU but also indicated that heifer rearing on semi-natural grasslands supports biodiversity conservation.

Using RM instead of GS in heifer diets raised GHG and lowered LU across all diet combinations. This can be attributed to a combination of factors, such as lower requirements for GS, lower crop yield for whole crop cereals compared with GS, and the higher input requirements (e.g., barley grains, straw for bedding) in RM. Lastly, GHG and LU trends did not always align; BYP reduced both, whereas DOM reduced GHG but increased LU. Together, these contrasting results emphasise evaluating both emissions and land requirements, considering regional land availability, biodiversity goals, and alternative LU opportunities.

6.3.2 Trade-offs, allocation, and system interactions

Study III enabled the results from Studies I and II to be interpreted in a different context and identified connections that were easy to miss when focusing on single animals or gases. For instance, Study II detected no animal-level CH_4 change when replacing part of GS with whole-crop cereal silage. However, at the farm level, RM can increase GHG mainly due to the effects of whole-crop cereal silage production on total crop yields, input intensity, and grain availability. Likewise, barley grain self-sufficiency was affected, with the dietary combination based on RM and BYP/DOM tending to increase on-farm barley gain use, thereby restricting the quantities of grain available for sale and altering both GHG and LU.

The choice of allocation is also important and can affect the results. In our study, feed CF and LU values were calculated using economic allocation, consistent with the underlying methodology of the animal trials (Study I). Whilst this allocation approach helps to maintain internal consistency and facilitates broader comparability, we acknowledge that the choice of allocation method significantly affects outcomes (van Hal et al. 2019b). Economic allocation assigns the majority of the environmental burden to the primary product, resulting in lower CF and LU values for co-products and by-products, and possibly favours the BYP diet combination. A mass or biophysical allocation could redistribute burdens and narrow differences between the diet combinations.

Lastly, the choice of warming metric can influence the interpretation of the results. We reported GWP100 values based on the IDF guidelines (2022) but also acknowledge that a metric that better captures the rate of change (e.g., GWP*; Lynch 2019) would place relatively more weight on persistent CO_2/N_2O cuts and the trajectory of CH_4 rather than its level at a point in time. Ultimately, methodological choices could have affected the amount of enteric CH_4. More specifically, enteric CH_4 emissions were calculated based on the predicted DMI by NorFor® (Volden 2011) and the CH_4 yield from Study I. The predicted DMI was higher for BYP and DOM than for COM, resulting in greater total CH_4. However, as mentioned earlier, DMI and CH_4 production were comparable in Studies I and II. Nevertheless, whilst enteric CH_4 is frequently the focus of sustainability discussions around dairy production, our results demonstrate that total system-level GHG emissions can be reduced even when CH_4 emissions slightly increase. This highlights the importance of assessing emissions at the whole-farm level rather than focusing solely on individual gases. More broadly, the results of Study III indicated that feed efficiency gains should be evaluated alongside CF and LU of the entire feed ration to better assess the environmental performance.

System vulnerability to extreme weather events also matters as this can limit roughage availability. Using whole crop cereal silage in heifer diets can buffer feed security when GS is scarce, yet farm-level GHG emissions increased when RM was used. Combining RM with a concentrate mix based on low CF ingredients (BYP, DOM) compensated for this increase and helped to maintain overall GHG emissions that were lower than the COM-GS baseline. This interaction further illustrates that decisions validated at animal scale (Studies I-II) must be tested at higher hierarchical levels to reveal possible interactions.

6.3.3 Practical implications and mitigation options

The findings of Study III showed that it is possible to achieve moderate GHG reductions (BYP: ~6%; DOM: ~2.9%) from a high-producing dairy farm through dietary interventions. Low CF concentrates (especially by-product-based and domestic low CF options) are immediately actionable interventions for lowering farm GHG without sacrificing milk output. However, more substantial GHG reduction requires complementary actions such as improved manure management, feed-loss reduction, better health and fertility (to lower replacement rates), and, where feasible, CH_4 inhibitors (3-NOP, *Asparagopsis spp*.; Van Gastelen et al. 2022; Angellotti et al. 2025) as adjuncts, not stand-alone fixes.

Some limitations of this study were that the results reflect a high-yielding Swedish system with fixed rotations and concentrate recipes and ingredient footprints drawn from aggregated datasets. Ultimately, Study III aimed to compare the dietary combination; thus, any future comparisons with our results should consider the effect of the underlying assumptions on the GHG emission intensity. Future work could include region-specific crop rotations, optimal use of N and P, and consideration for the seasonal availability of some of these ingredients. Accounting for soil-carbon dynamics can significantly influence the results, as seen in Study III's sensitivity analysis, for instance, cultivation on organic soils. Previous research has also demonstrated the importance of changes in soil carbon stocks when assessing dietary feeding strategies (Van Middelaar et al. 2013). A consequential LCA could better capture the opportunity cost of LU and the alternative use of these ingredients as well as expand system boundaries (e.g., including the rearing of sold livestock). Lastly, we acknowledge that the estimated reductions in farm-level GHG emissions are valid within an attributional LCA framework, which assumes that adopting this ration has a marginal effect on the broader food system. In this context, ingredient impacts are calculated using an economically allocated CF. However, under a consequential LCA perspective, widespread adoption may affect the demand for these ingredients, potentially altering their price, production patterns, and

LU, and resultingly changing their CF. Still, consequential LCAs generally have higher uncertainties since a larger system must be modelled and more assumptions are needed.

At the same time, it is important to acknowledge that LCA methodology presents certain limitations in capturing multifunctionality and ecosystem services. Attributional LCA, as applied here, treats milk as the primary output and may under-represent ecosystem services delivered by dairy, particularly from grazing semi-natural grasslands. In our system, approximately 18%-20% of the LU per kg ECM stems from these grasslands, which are partly maintained for biodiversity conservation. A multifunctional framing would treat biodiversity as a co-output. Several authors have proposed that a share of the GHG emissions should be allocated to such services based on the economic support associated with them (von Greyerz et al. 2023; Jardstedt et al. 2025). Adopting these approaches would not alter total GHG emissions or LU but would redistribute impacts across outputs. Therefore, sensitivity analyses that explicitly test alternative treatments of ecosystem services are recommended in future studies.

6.4 Regional-Level Assessment

Study IV assessed four scenarios in the year 2045 for Norrland: i) Food as Industry, ii) Food as Technology, iii) Food as Culture, and iv) Food Forgotten (Gordon et al. 2022). The results of this study can mark a starting point for future research utilising scenario analysis focusing on a specific geographic region and combining feed trial data and regional industry data.

6.4.1 Regional milk production and herd structure

In Food as Industry, milk yield per cow increased through intensification and concentrate-rich diets (COM). The total number of adult cattle remained comparable to the 2022 baseline, yet annual regional milk production increased by approximately 42%, reaching 2.92×10^8 kg ECM. Food as Technology was centred on by-products (BYP), which improved animal health and welfare, resulting in reduced replacement rates. Thus, the adult cattle herd decreased by 16% and the heifer numbers by 33% relative to 2022. Milk yield per cow decreased, resulting in a 45% reduction in the total ECM deliveries (1.13×10^8 kg) from baseline levels. Food as Culture prioritised domestic feeds (DOM) and grazing. Compared to the 2022 baseline, the adult cattle population increased by 8%, whilst replacement heifers declined by 14%, reflecting improved herd longevity. The annual regional milk production remained stable at 2.07×10^8 kg ECM, suggesting sustained production levels under more extensive and regionally integrated practices. The Food Forgotten largely phased out ruminants (93% reduction), achieving net zero emissions, with milk deliveries of just 0.21×10^8 kg ECM (90% reduction from 2022 levels).

6.4.2 GHG emissions, LU, and input dependency

Food as Industry achieved the second-lowest milk CF (0.41 kg $CO_{2\text{-eq}}$/kg ECM, including soil carbon sequestration), which is in accordance with previous findings that intensification can reduce emissions per unit of product (Wall et al. 2019). Despite the productivity gains, this scenario required higher feed inputs and a greater reliance on imported resources. Total GHG emissions decreased to 1.27×10^8 kg $CO_{2\text{-eq}}$, a 35% reduction compared to the 2022 baseline, indicating that production intensification, when paired with mitigation technologies, can yield substantial emission reductions. However, the increased reliance on feed imports suggested trade-offs between regional intensification and regional self-sufficiency, whilst the decrease in semi-natural grassland can negatively affect biodiversity.

In the Food as Technology scenario, total GHG emissions declined by a substantial 42%, to 1.13×10^8 kg $CO_{2\text{-eq}}$. However, this reduction in GHG emissions, although greater than the Food as Industry scenario, was accompanied by a strong decrease in cow productivity and therefore resulted in the highest milk CF (0.90 kg $CO_{2\text{-eq}}$/kg ECM including soil carbon sequestration). Under this scenario, dairy production became more extensive, with an increased reliance on semi-natural grasslands, thus maintaining current areas and biodiversity levels despite a smaller number of animals. The forage-based diets reduced feed imports, reflecting increased feed self-sufficiency and better use of the locally available biomass. Under this scenario, the freed-up arable land was afforested, which is beneficial for GHG mitigation but can negatively affect both the food system and the local biodiversity.

Under the Food as Culture scenario, the total GHG emissions declined to 1.78×10^8 kg $CO_{2\text{-eq}}$, a 9% reduction compared to 2022. This decrease resulted in a milk CF of 0.79 kg $CO_{2\text{-eq}}$/kg ECM, including soil carbon sequestration. Thus, this scenario achieved modest gains in terms of GHG reduction. However, the increased semi-natural grasslands and arable LU combined with high roughage diets and climate mitigation measures reflected a transition to regional feed autonomy and integration with cultural values.

The Food Forgotten scenario achieved net-zero GHG emissions from the dairy system. The drastic decrease in the number of animals freed up arable land, which in turn was repurposed for perennial grass-based biochar production. Although such a transition sharply decreased GHG emissions, it also reduced the sector's food output, affecting food security in the area. Additionally, semi-natural grassland use decreased by 92%, which negatively impacted biodiversity.

6.4.3 Policy relevance, limitations, and future research

Through these four scenarios, Study IV illustrated how different policy priorities, value systems, and technological choices may shape the future of dairy production in subarctic regions. Each scenario presented distinct trade-offs between production capacity, GHG emissions, LU, and input dependency. No single scenario optimised all goals. Food as Industry demonstrated that it is possible to increase dairy output whilst reducing emissions per unit of milk, but only at the cost of greater reliance on imported inputs and higher system vulnerability. Food as Technology reduced herd size and input use, achieving strong climate performance but at the expense of production volume. Food as Culture balanced climate mitigation with regional self-sufficiency, maintaining dairy output close to 2022 levels through grazing and domestically sourced feed. Food Forgotten, by contrast, represented a system transformation focused on net-zero GHG emissions rather than food output. These contrasting outcomes underscore the importance of aligning dairy systems' sustainability transitions with environmental targets and societal food system goals. The scenario framework serves as a valuable tool for stress-testing current trajectories and fostering discussion around the desired future role of animal agriculture in Sweden's net-zero emissions food strategy.

The analysis was constrained by scenario simplifications (one pelleted concentrate type per scenario), present-day performance and CH_4 parameters, and a limited focus on animal health, economics, and biodiversity. Beyond these points, dairy was also assessed without fully modelling crop production, dairy, and beef interactions. Moreover, the scenarios did not explicitly evaluate impacts on animal health, even though changes in feed quality, productivity targets, or management intensity may pose risks to fertility, metabolic balance, and welfare (e.g., Grandl et al. 2019). Future work should add spatially explicit biomass and yield projections under climate pathways, region- and season-specific ingredient footprints, more realistic rotations and soil-carbon dynamics, and consequential LCA to capture displaced land and alternative biomass uses, ideally scaling up to national comparisons of regional roles.

Finally, it is worth mentioning that LCA-based quantifications are useful for benchmarking and comparing options. Still, the results remain context-dependent, and their interpretation depends as much on assumptions and system boundaries as on the numerical outcomes. Attributional assessments are valuable for exploring mitigation potential, but they simplify LU processes and only focus on anthropogenic GHGs, thereby neglecting the role of reference ecosystems and baseline carbon dynamics (Del Prado et al. 2025). In the context of agriculture, the characterisation of the reference ecosystems, including wild animal composition and baseline GHG emissions, is particularly important (Thompson et al. 2023). The results are therefore contingent on the reference state chosen and may differ under consequential approaches that capture market feedback, displaced production, or alternative uses of biomass.

6.5 Contribution to the food system

Dairy cattle contribute directly to the food system by producing milk and meat, and indirectly by, for example, recycling P and N through manure. As ruminants, they upcycle human-inedible biomass (e.g., roughages, crop residues, and by-products, biomass from semi-natural grasslands and other non-arable land) into nutrient-dense foods (Place 2024). This function is enabled by microbial fermentation in the gastrointestinal tract, which also produces enteric CH_4. However, despite this upcycling ability, ruminant production can compete with food crops by using human-edible (HE) biomass (e.g., cereals) or occupying arable land.

6.5.1 Metrics

There is currently no universally accepted framework to quantify the contribution of ruminants to the food system. Mass-based metrics (e.g., feed conversion ratio) overlook the chemical composition of the consumed biomass, favouring monogastrics. Complementary indications based on the net-HE output better capture parameters such as the nutrient composition and bioavailability (e.g., DIAAS or human-digestible essential amino acids; Wilkinson 2011; Ertl et al. 2015; Patel et al. 2017). Moreover, the role of animal-derived foods is context-dependent. In settings with nutrient deficiencies, animal-sourced foods may play a key role in combating undernutrition, whereas in nutrient-dense diets, their marginal nutritional benefit may be lower (Sonesson et al. 2017; Bianchi et al. 2020; Hallström et al. 2022). Consequently, assessments of ruminant contributions should be tailored to regional dietary needs and food security goals, accounting for land productivity and opportunity cost of feed production, rather than relying solely on mass-based indicators.

6.5.2 Evidence from Studies III-IV

In Study III, farm-level ECM and LW outputs were fixed (Table 5); however, differences emerged in feed use and net-mass output. For instance, COM produced the most surplus barley grain (GS: 140 t DM/y; RM: 24 t DM/y) outperforming both BYP (GS: 113 t DM/y; RM: 0 t DM/y) and DOM (GS: 45 t DM/y; RM: 0 t DM/Y) in gross mass output. Using net-mass output (barley grain output minus concentrate feed input), the BYP-GS strategy performed the best, both in total and when normalised per $CO_{2\text{-eq}}$ or LU. In contrast, DOM performed the worst. Accounting for the potential HE fraction changed the ranking (results not shown). Using standard HE factors (roughages/minerals = 0; by-products ≈ 0.2; cereals ≈ 0.8; milk/meat = 1.0; Wilkinson 2011; Ertl et al. 2015), BYP-GS delivered the highest total net HE output and output per kg $CO_{2\text{-eq}}$ or per LU. On the other hand, DOM underperformed compared to COM.

In Study IV, the scenarios also showed these trade-offs (Table 7). Food as Industry increased regional milk and reduced total GHG. Still, reduced semi-natural grassland use increased the reliance on HE imports and thus yielded an approximately net-zero HE contribution. Food Forgotten achieved net-zero GHG, but with a very low net-HE contribution. By contrast, Food as Technology and Food as Culture relied more on roughage and semi-natural grasslands; although their GHG reductions were more moderate, both increased net food production at the regional scale.

6.5.3 Implications and research needs

Future evaluations should evaluate HE production, agroecology, and circularity, alongside environmental and LU opportunity-cost perspectives (Thompson et al. 2023). Ration assessment should consider how roughage sources fit within crop rotations and quantify soil carbon and biodiversity impacts. As milk yields per cow increase, the roughage share in dairy rations often decreases. From an agroecological and feed-food competition perspective, there may be an optimal milk yield that balances these dimensions. The Norrland scenarios demonstrate that feed choices can shift feed flows and LU beyond the region and that analyses should capture cross-regional spillovers. Future research should examine how eliminating or altering livestock numbers affects food-system resilience (Leroy et al. 2022). Whilst producing roughages on potentially arable land can contribute to food competition, grassland and rangeland soils store ~20% of global soil organic carbon (Conant 2012), and conversion to cropland can carry substantial carbon costs. For instance, from 2008 to 2012, an estimated 38.8 million t CO_2/yr were emitted due to grassland-to-cropland conversion in the USA (Spawn et al. 2019). Ultimately, identifying optimal herd sizes/species mixes and production intensities is highly dependent on the agroecological zone and local diet requirements, and it should be evaluated with spatially explicit territorial indicators.

Table 7. Comparison of results from Study IV evaluating regional production of milk and meat, regional imports of feed and human edible (HE) biomass, and Net balance in terms of dry matter (DM) and HE biomass DM in Norrland, Sweden, under the baseline (BAS), Food as Industry (IND), Food as Technology (TECH), Food as Culture (CUL), and Food Forgotten (FORG) scenarios.

	Regional production ($\times 10^7$ kg DM/y)		**Regional imports ($\times 10^7$ kg DM/y)**		**Net balance ($\times 10^7$ kg/y)**	
Scenario	Milk[1]	Meat[2]	Feed	HE Feed	DM	HE DM
BAS	2.55	0.06	5.33	2.21	-2.72	0.40
IND	3.60	0.06	9.00	3.66	-5.34	0.00
TECH	1.40	0.05	2.40	0.50	-0.95	0.95
CUL	2.55	0.06	3.97	1.37	-1.36	1.24
FORG	0.26	< 0.01	0.66	0.14	-0.40	0.12

[1]Calculated based on total regional milk production and assuming a milk dry matter content of 13%

[2]Calculated based on the total regional live weight and assuming a carcass dressing percentage of 60% and a carcass dry matter content of 25%

6.6 Policy and Practical Implications

This thesis demonstrates that feed-based mitigation of GHG emissions is technically feasible and practically implementable from a systems perspective. Rations formulated with low CF ingredients (by-products and suitable domestic crops) can lower farm-level GHG emissions without compromising productivity and can be implemented with existing equipment and routines.

Farm-level actions. Prioritising low CF ingredients in balanced dairy rations can decrease GHG emissions, aligning with national/EU climate targets. Combining CH_4-inhibiting additives and interventions that reduce feed losses, lower replacement rates, and improve manure management (e.g., capturing and combustion of produced CH_4 or anaerobic digester) can further reduce GHG emissions. Whole-crop cereal silage, when integrated in dairy heifer diets, can buffer GS shortages. When these diets are combined with low CF concentrates for dairy cows, they mitigate GHG emissions trade-offs.

Policy levers. Feed ration formulation is cost-driven, and thus the adoption of feed rations necessitates market and policy support. This can be in the form of: i) feed sustainability and traceability standards that disincentivise high CF or non-certified ingredients and align with EU traceability/deforestation rules; ii) region-specific support, acknowledging differences in land availability, roughage potential, and opportunity costs (e.g., roughage-based strategies and semi-natural grasslands in Norrland); and iii) investment in monitoring and advisory capacity (real-time feed composition, CH_4 recording, farmer/advisor training on GHG mitigation).

Scenario analysis. Study IV shows that single-metric instruments (e.g., GHG-reduction goals or herd caps) are subjected to trade-offs. Improving one target can worsen others, such as biodiversity, LU, or import dependence. Policy should therefore adopt multi-criteria objectives (GHG, LU, HE feed use, biodiversity, feed security) and requires a systems-level approach so that CH_4-oriented actions do not shift burdens upstream.

Implementation and the need for evidence. A priority in dairy research is improving decision quality and scalability through the following areas:

- Measurement and data integration. Advance farm-level measurement by integrating CH_4 sensing and real-time feed intake and composition (e.g., NIR) into routine workflows. This can provide the necessary data for whole-farm guidance. Since farming conditions (e.g., climate, feeding management, genetic selection) continuously change, feed evaluation and GHG emissions models must be regularly updated and recalibrated to remain accurate and relevant. This requires continuous integration and analysis of both research and empirical farm data to refine predictive models of feed intake, metabolism, productivity, and emissions.
- LCA methods and metrics. The results of this study enable an estimation of the farm-level GHG emissions and comparison of the feed combinations. However, extrapolating these results to different dairy production systems requires a consequential approach to better capture displaced LU, alternative biomass uses, and market feedback (including by-product price/availability effects). Incorporating region- and season-specific ingredient footprints, realistic crop rotations, and soil-carbon dynamics (including organic soils and sequestration) will increase the complexity of the analysis but allow for more informed comparisons. Ecosystem services (e.g., biodiversity from semi-natural grasslands) should be evaluated alongside food outputs where relevant.
- Equity and comparability. Whilst metrics such as GWP* better capture the atmospheric dynamics of short-lived GHG, they can produce less favourable results for regions where herds are expanding to meet food security needs than for regions where herds have stabilised or declined. To avoid inequitable comparisons, GWP* should be presented alongside GWP100, clearly reporting baseline and herd trends. Likewise, assessment of CF can be affected by allocation methods, temporal baselines, and country-of-origin averages, and thus requires consideration of the different agricultural conditions.
- Resilience and spillovers. Quantify year-to-year variation in crop production, feed shortages, price shocks, and extreme weather, and identify resilience thresholds. Track cross-regional spillovers

in GHG, LU, and HE-feed flows so that regional gains do not externalise costs elsewhere. Position heifer and youngstock nutrition within lifetime emissions and productivity trajectories.

Contribution and novelty of this work. This thesis: i) optimised rations on nutritional value and CF, comparing whole rations rather than isolated ingredients; ii) tested by-product based diets on high producing dairy cows (milk yield of up to 53.0 kg ECM/d); iii) used pelleted concentrates for both low-CF and compatibility with automated milking, enhancing on-farm applicability; iv) presented, to our knowledge, the first heifer trial with direct CH_4 measurements on whole-crop cereal silage; and v) grounded the LCA in measured trial data (intake, digestibility, CH_4), reducing the reliance on generic factors.

Adapting feeding and management can deliver GHG reductions without drastic livestock cuts, protecting livelihoods and domestic supply whilst simultaneously aligning with Swedish and EU climate objectives.

7. Conclusion

This research provided a science-based foundation for optimising dairy rations to balance productivity and sustainability. The results demonstrated that selecting feed ingredients with a low CF can significantly influence GHG emissions without compromising animal performance.

Animal performance and emissions

- It is possible to reduce GHG emissions associated with feed production without adverse effects on milk production and enteric CH_4 emissions from Swedish Holstein dairy cows in mid-lactation, yielding 43.3 ± 5.4 kg ECM/d.
- Integrating whole crop wheat silage to 50:50 (DM basis) proportions in GS-based diets of Swedish Holstein and Nordic Red dairy heifers has no effect on feed intake, growth rate, and enteric CH_4 emissions.

Farm-level implications

- Adopting a concentrate mix based on low-CF; by-product-based or domestically produced ingredients, can reduce the GHG emissions on a farm level for a given milk output.
- Decreasing GHG emissions from feed production by selecting a concentrate mix based on low CF ingredients did not affect total LU for a given milk output.

Regional sustainability trade-offs

- Scenario analysis specific to a geographical region, in this case Norrland, combining feed trial data and region industry data, can enhance understanding about the effects of management on milk production, herd structure, carbon import, LU, and CF.

Overall, this thesis underscores that sustainable feeding strategies can reduce the CF of dairy production in Sweden and contribute to a more resilient and resource-efficient dairy sector.

References

Angellotti, M., Lindberg, M., Ramin, M., Krizsan, S.J. & Danielsson, R. (2025). Asparagopsis taxiformis supplementation to mitigate enteric methane emissions in dairy cows—Effects on performance and metabolism. *Journal of Dairy Science*, 108 (3), 2503–2516. https://doi.org/10.3168/jds.2024-25258

Ardente, F. & Cellura, M. (2012). Economic Allocation in Life Cycle Assessment: The State of the Art and Discussion of Examples. *Journal of Industrial Ecology*, 16 (3), 387–398. https://doi.org/10.1111/j.1530-9290.2011.00434.x

Arthur, P.F., Barchia, I.M., Weber, C., Bird-Gardiner, T., Donoghue, K.A., Herd, R.M. & Hegarty, R.S. (2017). Optimizing test procedures for estimating daily methane and carbon dioxide emissions in cattle using short-term breath measures. *Journal of Animal Science*, 95 (2), 645. https://doi.org/10.2527/jas2016.0700

Beauchemin, K.A., Ungerfeld, E.M., Abdalla, A.L., Alvarez, C., Arndt, C., Becquet, P., Benchaar, C., Berndt, A., Mauricio, R.M., McAllister, T.A., Oyhantçabal, W., Salami, S.A., Shalloo, L., Sun, Y., Tricarico, J., Uwizeye, A., De Camillis, C., Bernoux, M., Robinson, T. & Kebreab, E. (2022). Invited review: Current enteric methane mitigation options. *Journal of Dairy Science*, 105 (12), 9297–9326. https://doi.org/10.3168/jds.2022-22091

Beede, D.K. (2013). Can animal agriculture be sustainable? In: Kebreab, E. (ed.) *Sustainable Animal Agriculture* (pp. 284–312). CABI International.

Bianchi, M., Strid, A., Winkvist, A., Lindroos, A.-K., Sonesson, U. & Hallström, E. (2020). Systematic Evaluation of Nutrition Indicators for Use within Food LCA Studies. *Sustainability*, 12 (21), 8992. https://doi.org/10.3390/su12218992

Bojovic, M. & McGregor, A. (2023). A review of megatrends in the global dairy sector: what are the socioecological implications? *Agriculture and Human Values*, 40 (1), 373–394. https://doi.org/10.1007/s10460-022-10338-x

Brodie, G., Bootes, N., Dunshea, F. & Leury, B. (2019). Microwave Processing of Animal Feed: A Brief Review. *Transactions of the ASABE*, 62 (3), 705–717. https://doi.org/10.13031/trans.13266

Cherif, C., Hassanat, F., Claveau, S., Girard, J., Gervais, R. & Benchaar, C. (2018). Faba bean (*Vicia faba*) inclusion in dairy cow diets: Effect on nutrient digestion, rumen fermentation, nitrogen utilization, methane production, and milk performance. *Journal of Dairy Science*, 101 (10), 8916–8928. https://doi.org/10.3168/jds.2018-14890

Clasen, J.B., Fikse, W.F., Ramin, M. & Lindberg, M. (2024). Effects of herd management decisions on dairy cow longevity, farm profitability, and emissions of enteric methane – a simulation study of milk and beef production. A*nimal*, 18 (2), 101051. https://doi.org/10.1016/j.animal.2023.101051

Conant, R.T. (2012). Grassland Soil Organic Carbon Stocks: Status, Opportunities, Vulnerability. In: Lal, R., Lorenz, K., Hüttl, R.F., Schneider, B.U., & Von Braun, J. (eds) *Recarbonization of the Biosphere* (pp. 275–302). Springer Netherlands. https://doi.org/10.1007/978-94-007-4159-1_13

Costa, M.P., Chadwick, D., Saget, S., Rees, R.M., Williams, M. & Styles, D. (2020). Representing crop rotations in life cycle assessment: a review of legume LCA studies. *The International Journal of Life Cycle Assessment*, 25 (10), 1942–1956. https://doi.org/10.1007/s11367-020-01812-x

Del Prado, A., Pauné, F., Serrano-Zulueta, R., Baez, J.C., Batalla, I., De Tomassi, C., Fries, R., Guzmán, J., Manzano, P., Márquez, C., Martínez-Cano, V., Pardo, G. & Yamat, L. (2025). An in-depth approach on ecological and social processes improve quantifying the climatic impact of food production. *PLOS Climate*, 4 (6), e0000655. https://doi.org/10.1371/journal.pclm.0000655

Deppermann, A., Havlík, P., Valin, H., Boere, E., Herrero, M., Vervoort, J. & Mathijs, E. (2018). The market impacts of shortening feed supply chains in Europe. *Food Security*, 10 (6), 1401–1410. https://doi.org/10.1007/s12571-018-0868-2

Donadia, A.B., Torres, R.N.S., Silva, H.M.D., Soares, S.R., Hoshide, A.K. & Oliveira, A.S.D. (2023). Factors Affecting Enteric Emission Methane and Predictive Models for Dairy Cows. *Animals*, 13 (11), 1857. https://doi.org/10.3390/ani13111857

Douglass, G.K. (1984). The meanings of agricultural sustainability. In: Douglass, G.K. (ed.) *Agricultural sustainability in a changing world order* (pp. 3–30). Westview Press.

Dressler, E.A., Bormann, J.M., Weaber, R.L. & Rolf, M.M. (2023). Characterization of the number of spot samples required for quantification of gas fluxes and metabolic heat production from grazing beef cows using a GreenFeed. *Journal of Animal Science*, 101, skad176. https://doi.org/10.1093/jas/skad176

El Khosht, F.F., Bergkvist, G., Dahlin, A.S., Watson, C.A., Forkman, J., Nilsson, J. & Öborn, I. (2025). Rotational grass-legume leys increase arable crop yields, particularly at low N fertiliser rates. *Field Crops Research*, 326, 109835. https://doi.org/10.1016/j.fcr.2025.109835

Ertl, P., Klocker, H., Hörtenhuber, S., Knaus, W. & Zollitsch, W. (2015). The net contribution of dairy production to human food supply: The case of Austrian

dairy farms. *Agricultural Systems*, 137, 119–125. https://doi.org/10.1016/j.agsy.2015.04.004
Ertl, P., Steinwidder, A., Schönauer, M., Krimberger, K., Knaus, W. & Zollitsch, W. (2016a). Net food production of different livestock: A national analysis for Austria including relative occupation of different land categories / Netto-Lebensmittelproduktion der Nutztierhaltung: Eine nationale Analyse für Österreich inklusive relativer Flächenbeanspruchung. Die Bodenkultur: *Journal of Land Management, Food and Environment*, 67 (2), 91–103. https://doi.org/10.1515/boku-2016-0009
Ertl, P., Zebeli, Q., Zollitsch, W. & Knaus, W. (2016b). Feeding of wheat bran and sugar beet pulp as sole supplements in high-forage diets emphasizes the potential of dairy cattle for human food supply. *Journal of Dairy Science*, 99 (2), 1228–1236. https://doi.org/10.3168/jds.2015-10285
European Commission (2019). The European Green Deal. (COM(2019) 640 final). European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640
European Parliament (2011). European Parliament resolution of 8 March 2011 on the EU strategy on adaptation to climate change (2010/2103(INI)). European Parliament. https://www.europarl.europa.eu/doceo/document/TA-7-2011-0084_EN.html [2025-09-24]
European Parliament (2018). Report on the implementation of the Paris Agreement and the EU Strategy on climate action (2018/2080(INI)). (A8-0121/2018). European Parliament. https://www.europarl.europa.eu/doceo/document/A-8-2018-0121_EN.html [2025-09-24]
European Parliament and Council of the European Union (2023). Regulation (EU) 2023/1115 of the European Parliament and of the Council of 31 May 2023 on the making available on the Union market and the export from the Union of certain commodities and products associated with deforestation and forest degradation. Official Journal of the European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R1115 [2025-10-03]
European Parliamentary Research Service (2023). The European Green Deal: Key to sustainable future? (EPRS_BRI(2023)739328). European Parliament. https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/739328/EPRS_BRI(2023)739328_EN.pdf [2025-09-24]
FAO (2024). Greenhouse gas emissions from agrifood systems – *Global, regional and country trends, 2000–2022*. (FAOSTAT Analytical Brief No. 94). https://openknowledge.fao.org/handle/20.500.14283/cd3167en
FAO (2025a). FAOSTAT – Crops and Livestock Products. https://www.fao.org/faostat/en/#data/QCL/visualize [2025-09-23]

FAO (2025b). GLEAM 3 – Global Livestock Environmental Assessment Model. Food and Agriculture Organization of the United Nations. https://foodandagricultureorganization.shinyapps.io/GLEAMV3_Public/ [2025-09-23]

Fleischer, P., Metzner, M., Beyerbach, M., Hoedemaker, M. & Klee, W. (2001). The Relationship Between Milk Yield and the Incidence of Some Diseases in Dairy Cows. *Journal of Dairy Science*, 84 (9), 2025–2035. https://doi.org/10.3168/jds.S0022-0302(01)74646-2

Flysjö, A., Henriksson, M., Cederberg, C., Ledgard, S. & Englund, J.-E. (2011). The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden. *Agricultural Systems*, 104 (6), 459–469. https://doi.org/10.1016/j.agsy.2011.03.003

Frischknecht, R., Althaus, H.-J., Bauer, C., Doka, G., Heck, T., Jungbluth, N., Kellenberger, D. & Nemecek, T. (2007). The Environmental Relevance of Capital Goods in Life Cycle Assessments of Products and Services. *International Journal of Life Cycle Assessment,* 12 (Special Issue 1), 7–17.

Gerber, P., Vellinga, T., Opio, C. & Steinfeld, H. (2011). Productivity gains and greenhouse gas emissions intensity in dairy systems. *Livestock Science*, 139 (1–2), 100–108. https://doi.org/10.1016/j.livsci.2011.03.012

GFLI (2019). Global Feed LCA Institute Feed Dataset. https://globalfeedlca.org/ [2021-11-19]

Gordon, L.J., Holmgren, K.E., Bengtsson, J., Persson, U.M., Peterson, G.D., Röös, E., Wood, A., Avlstad, R., Basnet, S., Bunge, A.C., Jonell, M. & Fetzer, I. (2022). Mistra Food Futures Report #1. *Food as Industry, Food Tech or Culture, or Even Food Forgotten?: A Report on Scenario Skeletons of Swedish Food Futures*. (Mistra Food Futures Report #1). Swedish University of Agricultural Sciences (SLU).

Government of Sweden (2017). Climate Act (Klimatlagen). (SFS 2017:720). Government Offices of Sweden. https://rkrattsbaser.gov.se/sfst?bet=2017:720

Graddy-Lovelace, G. (2021). Farmer and non-farmer responsibility to each other: Negotiating the social contracts and public good of agriculture. *Journal of Rural Studies*, 82, 531–541. https://doi.org/10.1016/j.jrurstud.2020.08.044

Grandl, F., Furger, M., Kreuzer, M. & Zehetmeier, M. (2019). Impact of longevity on greenhouse gas emissions and profitability of individual dairy cows analysed with different system boundaries. *Animal*, 13 (1), 198–208. https://doi.org/10.1017/S175173111800112X

von Greyerz, K., Tidåker, P., Karlsson, J.O. & Röös, E. (2023). A large share of climate impacts of beef and dairy can be attributed to ecosystem services other than food production. *Journal of Environmental Management*, 325, 116400. https://doi.org/10.1016/j.jenvman.2022.116400

Guerci, M., Knudsen, M.T., Bava, L., Zucali, M., Schönbach, P. & Kristensen, T. (2013). Parameters affecting the environmental impact of a range of dairy farming systems in Denmark, Germany and Italy. *Journal of Cleaner Production*, 54, 133–141. https://doi.org/10.1016/j.jclepro.2013.04.035

Guinguina, A., Krizsan, S.J. & Huhtanen, P. (2021). Postpartum responses of dairy cows supplemented with cereal grain or fibrous by-product concentrate. *Livestock Science*, 248, 104506. https://doi.org/10.1016/j.livsci.2021.104506

Hagemann, M., Ndambi, A., Hemme, T. & Latacz-Lohmann, U. (2012). Contribution of milk production to global greenhouse gas emissions: An estimation based on typical farms. *Environmental Science and Pollution Research*, 19 (2), 390–402. https://doi.org/10.1007/s11356-011-0571-8

van Hal, O., de Boer, I.J.M., Muller, A., de Vries, S., Erb, K.-H., Schader, C., Gerrits, W.J.J. & van Zanten, H.H.E. (2019a). Upcycling food leftovers and grass resources through livestock: Impact of livestock system and productivity. *Journal of Cleaner Production*, 219, 485–496. https://doi.org/10.1016/j.jclepro.2019.01.329

van Hal, O., Weijenberg, A.A.A., de Boer, I.J.M. & van Zanten, H.H.E. (2019b). Accounting for feed-food competition in environmental impact assessment: Towards a resource efficient food-system. *Journal of Cleaner Production*, 240, 118241. https://doi.org/10.1016/j.jclepro.2019.118241

Hallström, E., Davis, J., Håkansson, N., Ahlgren, S., Åkesson, A., Wolk, A. & Sonesson, U. (2022). Dietary environmental impacts relative to planetary boundaries for six environmental indicators – A population-based study. *Journal of Cleaner Production*, 373, 133949. https://doi.org/10.1016/j.jclepro.2022.133949

Hammond, K.J., Crompton, L.A., Bannink, A., Dijkstra, J., Yáñez-Ruiz, D.R., O'Kiely, P., Kebreab, E., Eugène, M.A., Yu, Z., Shingfield, K.J., Schwarm, A., Hristov, A.N. & Reynolds, C.K. (2016). Review of current in vivo measurement techniques for quantifying enteric methane emission from ruminants. *Animal Feed Science and Technology*, 219, 13–30. https://doi.org/10.1016/j.anifeedsci.2016.05.018

Henriksson, M. (2014). *Greenhouse gas emissions from Swedish milk production: towards climate-smart milk production = Växthusgasutsläpp från svensk mjölkproduktion: mot en klimatsmart mjölkproduktion*. Diss. Swedish University of Agricultural Sciences. Department of Biosystems and Technology

Henriksson, M., Cederberg, C. & Swensson, C. (2014). Carbon footprint and land requirement for dairy herd rations: impacts of feed production practices and regional climate variations. *Animal*, 8 (8), 1329–1338. https://doi.org/10.1017/S1751731114000627

Hoffman, P.C., Weigel, K.A. & Wernberg, R.M. (2008). Evaluation of Equations to Predict Dry Matter Intake of Dairy Heifers. *Journal of Dairy Science*, 91 (9), 3699–3709. https://doi.org/10.3168/jds.2007-0644

Hristov, A.N., Bannink, A., Battelli, M., Belanche, A., Cajarville Sanz, M.C., Fernandez-Turren, G., Garcia, F., Jonker, A., Kenny, D.A., Lind, V., Meale, S.J., Meo Zilio, D., Muñoz, C., Pacheco, D., Peiren, N., Ramin, M., Rapetti, L., Schwarm, A., Stergiadis, S., Theodoridou, K., Ungerfeld, E.M., Van Gastelen, S., Yáñez-Ruiz, D.R., Waters, S.M. & Lund, P. (2025). Feed additives for methane mitigation: Recommendations for testing enteric methane-mitigating feed additives in ruminant studies. *Journal of Dairy Science*, 108 (1), 322–355. https://doi.org/10.3168/jds.2024-25050

Huhtanen, P., Ramin, M. & Hristov, A.N. (2019). Enteric methane emission can be reliably measured by the GreenFeed monitoring unit. *Livestock Science*, 222, 31–40. https://doi.org/10.1016/j.livsci.2019.01.017

Huhtanen, P., Vanhatalo, A. & Varvikko, T. (2002). Effects of Abomasal Infusions of Histidine, Glucose, and Leucine on Milk Production and Plasma Metabolites of Dairy Cows Fed Grass Silage Diets. *Journal of Dairy Science*, 85 (1), 204–216. https://doi.org/10.3168/jds.S0022-0302(02)74069-1

IDF (2022). *The IDF global Carbon Footprint standard for the dairy sector*. International Dairy Federation (IDF) AISBL. https://doi.org/10.56169/FKRK7166

Ineichen, S., Schenker, U., Nemecek, T. & Reidy, B. (2022). Allocation of environmental burdens in dairy systems: Expanding a biophysical approach for application to larger meat-to-milk ratios. *Livestock Science*, 261, 104955. https://doi.org/10.1016/j.livsci.2022.104955

Ingvartsen, K.L. (2006). Feeding- and management-related diseases in the transition cow. *Animal Feed Science and Technology*, 126 (3–4), 175–213. https://doi.org/10.1016/j.anifeedsci.2005.08.003

Ishler, V.A. (2023). *Interpretation of Milk Urea Nitrogen (MUN) Values*. PennState Extension. https://extension.psu.edu/interpretation-of-milk-urea-nitrogen-mun-values [2025-07-30]

Jamali, H., Barkema, H.W., Jacques, M., Lavallée-Bourget, E.-M., Malouin, F., Saini, V., Stryhn, H. & Dufour, S. (2018). Invited review: Incidence, risk factors, and effects of clinical mastitis recurrence in dairy cows. *Journal of Dairy Science*, 101 (6), 4729–4746. https://doi.org/10.3168/jds.2017-13730

Janssen, P.H. (2010). Influence of hydrogen on rumen methane formation and fermentation balances through microbial growth kinetics and fermentation thermodynamics. *Animal Feed Science and Technology*, 160 (1–2), 1–22. https://doi.org/10.1016/j.anifeedsci.2010.07.002

Jardstedt, M., Parvin, N., Wallman, M. & Hessle, A. (2025). Greenhouse gas emissions from pasture-based beef production—should they only burden the meat? *Proceedings of the 76th Annual Meeting of the European Federation of Animal Science (EAAP)*, Innsbruck, Austria, 2025. 506. Wageningen Academic Publishers

Johnston, D.J., Theodoridou, K., Gordon, A.W., Yan, T., McRoberts, W.C. & Ferris, C.P. (2019). Field bean inclusion in the diet of early-lactation dairy cows: Effects on performance and nutrient utilization. *Journal of Dairy Science*, 102 (12), 10887–10902. https://doi.org/10.3168/jds.2019-16513

Karlsson, J., Ramin, M., Kass, M., Lindberg, M. & Holtenius, K. (2019). Effects of replacing wheat starch with glycerol on methane emissions, milk production, and feed efficiency in dairy cows fed grass silage-based diets. *Journal of Dairy Science*, 102 (9), 7927–7935. https://doi.org/10.3168/jds.2018-15629

Karlsson, J., Spörndly, R., Lindberg, M. & Holtenius, K. (2018). Replacing human-edible feed ingredients with by-products increases net food production efficiency in dairy cows. *Journal of Dairy Science*, 101 (8), 7146–7155. https://doi.org/10.3168/jds.2017-14209

Karlsson, J.O., Robling, H., Cederberg, C., Spörndly, R., Lindberg, M., Martiin, C., Ardfors, E. & Tidåker, P. (2023). What can we learn from the past? Tracking sustainability indicators for the Swedish dairy sector over 30 years. *Agricultural Systems*, 212, 103779. https://doi.org/10.1016/j.agsy.2023.103779

Khan, M.A. (1995). Sustainable development: The key concepts, issues and implications. Keynote paper given at the international sustainable development research conference, 27–29 march 1995, Manchester, UK. *Sustainable Development*, 3 (2), 63–69. https://doi.org/10.1002/sd.3460030203

Lana, R.P., Russell, J.B. & Van Amburgh, M.E. (1998). The role of pH in regulating ruminal methane and ammonia production. *Journal of Animal Science*, 76 (8), 2190. https://doi.org/10.2527/1998.7682190x

Larson, R.L. (2007). Heifer Development: Reproduction and Nutrition. Veterinary Clinics of North America: *Food Animal Practice*, 23 (1), 53–68. https://doi.org/10.1016/j.cvfa.2006.11.003

Lavery, A., Craig, A., Gordon, A.W., White, A., Barkley, N. & Ferris, C.P. (2025). Reducing dietary crude protein levels while meeting metabolizable protein requirements: Performance of dairy cows over a full lactation period. *Journal of Dairy Science*, 108 (2), 1451–1473. https://doi.org/10.3168/jds.2024-25405

Leroy, F., Abraini, F., Beal, T., Dominguez-Salas, P., Gregorini, P., Manzano, P., Rowntree, J. & van Vliet, S. (2022). Animal board invited review: Animal source foods in healthy, sustainable, and ethical diets – An argument against drastic limitation of livestock in the food system. *Animal*, 16 (3), 100457. https://doi.org/10.1016/j.animal.2022.100457

Lovarelli, D., Bovo, M., Giannone, C., Santolini, E., Tassinari, P. & Guarino, M. (2024). Reducing life cycle environmental impacts of milk production through precision livestock farming. *Sustainable Production and Consumption*, 51, 303–314. https://doi.org/10.1016/j.spc.2024.09.021

Lynch, J. (2019). *Agricultural methane and its role as a greenhouse gas*. Food Climate Research Network. https://doi.org/10.56661/0f7f7b1e

McDonald, P., Edwards, R.A., Greenhalgh, J.F.D., Morgan, C.A., Sinclair, L.A. & Wilkinson, R.G. (2022). *Animal nutrition* (8th ed.). Pearson.

Meijaard, E., Brooks, T.M., Carlson, K.M., Slade, E.M., Garcia-Ulloa, J., Gaveau, D.L.A., Lee, J.S.H., Santika, T., Juffe-Bignoli, D., Struebig, M.J., Wich, S.A., Ancrenaz, M., Koh, L.P., Zamira, N., Abrams, J.F., Prins, H.H.T., Sendashonga, C.N., Murdiyarso, D., Furumo, P.R., Macfarlane, N., Hoffmann, R., Persio, M., Descals, A., Szantoi, Z. & Sheil, D. (2020). The environmental impacts of palm oil in context. *Nature Plants*, 6 (12), 1418–1426. https://doi.org/10.1038/s41477-020-00813-w

Mills, J.A.N., Kebreab, E., Yates, C.M., Crompton, L.A., Cammell, S.B., Dhanoa, M.S., Agnew, R.E. & France, J. (2003). Alternative approaches to predicting methane emissions from dairy cows. *Journal of Animal Science*, 81 (12), 3141–3150. https://doi.org/10.2527/2003.81123141x

Mogensen, L., Kristensen, T., Nguyen, T.L.T., Knudsen, M.T. & Hermansen, J.E. (2014). Method for calculating carbon footprint of cattle feeds – including contribution from soil carbon changes and use of cattle manure. *Journal of Cleaner Production*, 73, 40–51. https://doi.org/10.1016/j.jclepro.2014.02.023

Montes, F., Meinen, R., Dell, C., Rotz, A., Hristov, A.N., Oh, J., Waghorn, G., Gerber, P.J., Henderson, B., Makkar, H.P.S. & Dijkstra, J. (2013). Special topics— Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options. *Journal of Animal Science*, 91 (11), 5070–5094. https://doi.org/10.2527/jas.2013-6584

Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C. & Gerber, P. (2017). Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. *Global Food Security*, 14, 1–8. https://doi.org/10.1016/j.gfs.2017.01.001

Mottet, A., Teillard, F., Boettcher, P., De' Besi, G. & Besbes, B. (2018). Review: Domestic herbivores and food security: current contribution, trends and challenges for a sustainable development. *Animal*, 12, S188–S198. https://doi.org/10.1017/s1751731118002215

Mueller-Harvey, I., Bee, G., Dohme-Meier, F., Hoste, H., Karonen, M., Kölliker, R., Lüscher, A., Niderkorn, V., Pellikaan, W.F., Salminen, J.-P., Skøt, L., Smith, L.M.J., Thamsborg, S.M., Totterdell, P., Wilkinson, I., Williams, A.R., Azuhnwi, B.N., Baert, N., Brinkhaus, A.G., Copani, G., Desrues, O., Drake, C., Engström, M., Fryganas, C., Girard, M., Huyen, N.T., Kempf, K., Malisch, C., Mora-Ortiz, M., Quijada, J., Ramsay, A., Ropiak, H.M. & Waghorn, G.C. (2019). Benefits of Condensed Tannins in Forage Legumes Fed to Ruminants: Importance of Structure, Concentration, and Diet Composition. *Crop Science*, 59 (3), 861–885. https://doi.org/10.2135/cropsci2017.06.0369

Muscat, A., De Olde, E.M., Ripoll-Bosch, R., Van Zanten, H.H.E., Metze, T.A.P., Termeer, C.J.A.M., Van Ittersum, M.K. & De Boer, I.J.M. (2021). Publisher Correction: Principles, drivers and opportunities of a circular bioeconomy. *Nature Food*, 2 (9), 742–742. https://doi.org/10.1038/s43016-021-00371-0

Newbold, C.J., De La Fuente, G., Belanche, A., Ramos-Morales, E. & McEwan, N.R. (2015). The Role of Ciliate Protozoa in the Rumen. *Frontiers in Microbiology*, 6, 1313. https://doi.org/10.3389/fmicb.2015.01313

Nguyen, B.T., Briggs, K.R., Eicker, S., Overton, M. & Nydam, D.V. (2022). Herd turnover rate reexamined: a tool for improving profitability, welfare, and sustainability. *American Journal of Veterinary Research*, 1–6. https://doi.org/10.2460/ajvr.22.10.0177

Nielsen, N.I., Volden, H., Åkerlind, M., Brask, M., Hellwing, A.L.F., Storlien, T. & Bertilsson, J. (2013). A prediction equation for enteric methane emission from dairy cows for use in NorFor. *Acta Agriculturae Scandinavica, Section A – Animal Science*, 63 (3), 126–130. https://doi.org/10.1080/09064702.2013.851275

Niu, P., Schwarm, A., Bonesmo, H., Kidane, A., Aspeholen Åby, B., Storlien, T.M., Kreuzer, M., Alvarez, C., Sommerseth, J.K. & Prestløkken, E. (2021). A Basic Model to Predict Enteric Methane Emission from Dairy Cows and Its Application to Update Operational Models for the National Inventory in Norway. *Animals*, 11 (7), 1891. https://doi.org/10.3390/ani11071891

Nousiainen, J., Shingfield, K.J. & Huhtanen, P. (2004). Evaluation of Milk Urea Nitrogen as a Diagnostic of Protein Feeding. *Journal of Dairy Science*, 87 (2), 386–398. https://doi.org/10.3168/jds.S0022-0302(04)73178-1

O'Brien, D., Geoghegan, A., McNamara, K. & Shalloo, L. (2016). How can grass-based dairy farmers reduce the carbon footprint of milk? *Animal Production Science*, 56 (3), 495. https://doi.org/10.1071/AN15490

Opdenbosch, H. (2025). *Institutional and behavioural drivers of sustainable farming uptake*. Diss. Swedish University of Agricultural Sciences.

Pang, D., Yan, T., Trevisi, E. & Krizsan, S.J. (2018). Effect of grain- or by-product-based concentrate fed with early- or late-harvested first-cut grass silage on dairy cow performance. *Journal of Dairy Science*, 101 (8), 7133–7145. https://doi.org/10.3168/jds.2018-14449

Patel, M., Sonesson, U. & Hessle, A. (2017). Upgrading plant amino acids through cattle to improve the nutritional value for humans: effects of different production systems. A*nimal*, 11 (3), 519–528. https://doi.org/10.1017/S1751731116001610

Patra, A.K. (2013). The effect of dietary fats on methane emissions, and its other effects on digestibility, rumen fermentation and lactation performance in cattle: A meta-analysis. *Livestock Science*, 155 (2–3), 244–254. https://doi.org/10.1016/j.livsci.2013.05.023

Place, S.E. (2024). Examining the role of ruminants in sustainable food systems. *Grass and Forage Science*, 79 (2), 135–143. https://doi.org/10.1111/gfs.12673

Posit Team (2024). *RStudio: Integrated Development Environment for R*. [Computer Software]. Posit Software PBC. http://www.posit.co/

R Core Team (2022). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org

Ramin, M. & Huhtanen, P. (2013). Development of equations for predicting methane emissions from ruminants. *Journal of Dairy Science*, 96 (4), 2476–2493. https://doi.org/10.3168/jds.2012-6095

Regeringskansliet (2025). *Livsmedelsstrategin 2.0*. Regeringskansliet. https://www.regeringen.se/rattsliga-dokument/departementsserien-och-promemorior/2025/03/livsmedelsstrategin-2.0 [2025-08-04]

Reumaux, R., Chopin, P., Bergkvist, G., Watson, C.A. & Öborn, I. (2023). Land Parcel Identification System (LPIS) data allows identification of crop sequence patterns and diversity in organic and conventional farming systems. *European Journal of Agronomy*, 149, 126916. https://doi.org/10.1016/j.eja.2023.126916

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F., Drüke, M., Fetzer, I., Bala, G., Von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., Petri, S., Porkka, M., Rahmstorf, S., Schaphoff, S., Thonicke, K., Tobian, A., Virkki, V., Wang-Erlandsson, L., Weber, L. & Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, 9 (37). https://doi.org/10.1126/sciadv.adh2458

Rittel, H.W.J. & Webber, M.M. (1973). Dilemmas in a general theory of planning. *Policy Sciences*, 4 (2), 155–169. https://doi.org/10.1007/bf01405730

RKFS (2021). *Rules for calculation and communication of climate impact for feed in Sweden [Regler för beräkning och kommunikation av klimatpåverkan för foder i Sverige]*. https://www.foderochspannmal.se/_files/ugd/90417e_e487c792c7484ef881f2a8f3a3da96d9.pdf [2022-02-14]

Roche, S.M., Renaud, D.L., Saraceni, J., Kelton, D.F. & DeVries, T.J. (2024). Invited review: Prevalence, risk factors, treatment, and barriers to best practice adoption for lameness and injuries in dairy cattle—A narrative review. *Journal of Dairy Science*, 107 (6), 3347–3366. https://doi.org/10.3168/jds.2023-23870

Röös, E., Patel, M., Spångberg, J., Carlsson, G. & Rydhmer, L. (2016). Limiting livestock production to pasture and by-products in a search for sustainable diets. *Food Policy*, 58, 1–13. https://doi.org/10.1016/j.foodpol.2015.10.008

Rustas, B. -O., Nadeau, E. & Johnsson, S. (2009). Effect of stage of maturity of whole-crop barley on intake and liveweight gain by dairy steers differing in initial live weight. *Grass and Forage Science*, 64 (3), 227–235. https://doi.org/10.1111/j.1365-2494.2009.00688.x

Rustas, B.-O., Bertilsson, J., Martinsson, K., Elverstedt, T. & Nadeau, E. (2011). Intake and digestion of whole-crop barley and wheat silages by dairy heifers. *Journal of Animal Science*, 89 (12), 4134–4141. https://doi.org/10.2527/jas.2010-3585

Rustas, B.-O., Nørgaard, P., Jalali, A.R. & Nadeau, E. (2010). Effects of physical form and stage of maturity at harvest of whole-crop barley silage on intake, chewing activity, diet selection and faecal particle size of dairy steers. *Animal*, 4 (1), 67–75. https://doi.org/10.1017/S1751731109990887

Sasu-Boakye, Y., Cederberg, C. & Wirsenius, S. (2014). Localising livestock protein feed production and the impact on land use and greenhouse gas emissions. *Animal*, 8 (8), 1339–1348. https://doi.org/10.1017/S1751731114001293

Scherer, L., Tomasik, B., Rueda, O. & Pfister, S. (2018). Framework for integrating animal welfare into life cycle sustainability assessment. The International *Journal of Life Cycle Assessment*, 23 (7), 1476–1490. https://doi.org/10.1007/s11367-017-1420-x

Schröder, U.J. & Staufenbiel, R. (2006). Invited Review: Methods to Determine Body Fat Reserves in the Dairy Cow with Special Regard to Ultrasonographic Measurement of Backfat Thickness. *Journal of Dairy Science*, 89 (1), 1–14. https://doi.org/10.3168/jds.S0022-0302(06)72064-1

van Soest, P.J. (1994). Nutritional Ecology of the Ruminant (2nd ed). Cornell University Press. Comstock Bk

Sonesson, U., Davis, J., Flysjö, A., Gustavsson, J. & Witthöft, C. (2017). Protein quality as functional unit – A methodological framework for inclusion in life cycle assessment of food. *Journal of Cleaner Production*, 140, 470–478. https://doi.org/10.1016/j.jclepro.2016.06.115

Sorley, M., Casey, I., Styles, D., Merino, P., Trindade, H., Mulholland, M., Resch Zafra, C., Keatinge, R., Le Gall, A., O'Brien, D. & Humphreys, J. (2024). Factors influencing the carbon footprint of milk production on dairy farms with different feeding strategies in western Europe. *Journal of Cleaner Production*, 435, 140104. https://doi.org/10.1016/j.jclepro.2023.140104

Spawn, S.A., Lark, T.J. & Gibbs, H.K. (2019). Carbon emissions from cropland expansion in the United States. *Environmental Research Letters*, 14 (4), 045009. https://doi.org/10.1088/1748-9326/ab0399

Spörndly, R., Bergkvist, G., Nilsdotter-Linde, N. & Eriksson, T. (2019). *Ersättningsfoder till nötkreatur vid grovfoderbrist*. (Report 301). Institution: Institutionen för husdjurens utfodring och vård, Swedish University of Agricultural Sciences (SLU). ISSN 0347-9838, ISRN SLU-HUV-R-301-SE.

Statistics Sweden (2018). *Production of cereals, dried pulses, oilseed crops and temporary grasses 2018. Preliminary statistics for counties and the whole country*. Statistics Sweden. https://www.scb.se/en/finding-statistics/statistics-by-subject-area/agriculture-forestry-and-fishery/agricultural-production/production-of-cereals-dried-pulses-and-oil-seeds/pong/statistical-news/production-of-cereals-dried-pulses-oilseed-crops-and-temporary-grasses-2018.-preliminary-statistics-for-counties-and-the-whole-country [2025-01-07]

Thompson, L., Rowntree, J., Windisch, W., Waters, S.M., Shalloo, L. & Manzano, P. (2023). Ecosystem management using livestock: embracing diversity and respecting ecological principles. *Animal Frontiers*, 13 (2), 28–34. https://doi.org/10.1093/af/vfac094

United Nations (2015). *Paris Agreement*. United Nations.

Van Breukelen, A.E., Aldridge, M.N., Veerkamp, R.F., Koning, L., Sebek, L.B. & De Haas, Y. (2023). Heritability and genetic correlations between enteric methane production and concentration recorded by GreenFeed and sniffers on dairy cows. *Journal of Dairy Science*, 106 (6), 4121–4132. https://doi.org/10.3168/jds.2022-22735

Van Gastelen, S., Dijkstra, J. & Bannink, A. (2019). Are dietary strategies to mitigate enteric methane emission equally effective across dairy cattle, beef cattle, and sheep? *Journal of Dairy Science*, 102 (7), 6109–6130. https://doi.org/10.3168/jds.2018-15785

Van Gastelen, S., Dijkstra, J., Heck, J.M.L., Kindermann, M., Klop, A., De Mol, R., Rijnders, D., Walker, N. & Bannink, A. (2022). Methane mitigation potential of 3-nitrooxypropanol in lactating cows is influenced by basal diet composition. *Journal of Dairy Science*, 105 (5), 4064–4082. https://doi.org/10.3168/jds.2021-20782

Van Kessel, J. (1996). The effect of pH on ruminal methanogenesis. *FEMS Microbiology Ecology*, 20 (4), 205–210. https://doi.org/10.1016/0168-6496(96)00030-X

Van Knegsel, A.T.M., Van Den Brand, H., Dijkstra, J. & Kemp, B. (2007). Effects of dietary energy source on energy balance, metabolites and reproduction variables in dairy cows in early lactation. *Theriogenology*, 68, S274–S280. https://doi.org/10.1016/j.theriogenology.2007.04.043

Van Middelaar, C.E., Berentsen, P.B.M., Dijkstra, J. & De Boer, I.J.M. (2013). Evaluation of a feeding strategy to reduce greenhouse gas emissions from dairy farming: The level of analysis matters. *Agricultural Systems*, 121, 9–22. https://doi.org/10.1016/j.agsy.2013.05.009

Van Selm, B., Frehner, A., De Boer, I.J.M., Van Hal, O., Hijbeek, R., Van Ittersum, M.K., Talsma, E.F., Lesschen, J.P., Hendriks, C.M.J., Herrero, M. & Van Zanten, H.H.E. (2022). Circularity in animal production requires a change in the EAT-Lancet diet in Europe. *Nature Food*, 3 (1), 66–73. https://doi.org/10.1038/s43016-021-00425-3

Van Zanten, H.H.E., Van Ittersum, M.K. & De Boer, I.J.M. (2019). The role of farm animals in a circular food system. *Global Food Security*, 21, 18–22. https://doi.org/10.1016/j.gfs.2019.06.003

Vanhatalo, A., Huhtanen, P., Toivonen, V. & Varvikko, T. (1999). Response of Dairy Cows Fed Grass Silage Diets to Abomasal Infusions of Histidine Alone or in Combinations with Methionine and Lysine. *Journal of Dairy Science*, 82 (12), 2674–2685. https://doi.org/10.3168/jds.S0022-0302(99)75524-4

Växa Sweden (2008). IndividRAM: *För ökad lönsamhet* (Program version 6.34 (6.3.4.8), Database version 6.65) [Computer software]. Växa Sweden. https://www.vxa.se/ [2021-11-11]

Volden, H. (ed.) (2011). *NorFor – The Nordic feed evaluation system*. Brill | Wageningen Academic. https://doi.org/10.3920/978-90-8686-718-9

Von Soosten, D., Meyer, U., Flachowsky, G. & Dänicke, S. (2020). Dairy Cow Health and Greenhouse Gas Emission Intensity. *Dairy*, 1 (1), 20–29. https://doi.org/10.3390/dairy1010003

Wall, A.M., Campbell, D.I., Mudge, P.L., Rutledge, S. & Schipper, L.A. (2019). Carbon budget of an intensively grazed temperate grassland with large quantities of imported supplemental feed. *Agriculture, Ecosystems & Environment*, 281, 1–15. https://doi.org/10.1016/j.agee.2019.04.019

Wallsten, J., Bertilsson, J., Nadeau, E. & Martinsson, K. (2010). Digestibility of whole-crop barley and oat silages in dairy heifers. *Animal*, 4 (3), 432–438. https://doi.org/10.1017/S1751731109991212

Wallsten, J., Nadeau, E., Bertilsson, J. & Martinsson, K. (2009). Voluntary intake and diet selection by dairy heifers fed ensiled whole-crop barley and oats harvested at different stages of maturity. *Livestock Science*, 122 (1), 94–98. https://doi.org/10.1016/j.livsci.2008.07.031

Wilkinson, J.M. (2011). Re-defining efficiency of feed use by livestock. *Animal*, 5 (7), 1014–1022. https://doi.org/10.1017/S175173111100005X

Yan, T., Mayne, C.S. & Porter, M.G. (2006). Effects of dietary and animal factors on methane production in dairy cows offered grass silage-based diets. *International Congress Series*, 1293, 123–126. https://doi.org/10.1016/j.ics.2006.02.024

Popular science summary

Climate change requires the reduction of greenhouse gas emissions from all sectors of society, including food production. Dairy farming provides nutrient-dense foods but constitutes a major source of emissions within the agricultural sector. The sector has already made progress by improving animal productivity and testing additives that decrease methane, but more solutions are needed.

This thesis investigated how ration formulation using ingredients with a low carbon footprint can reduce total emissions whilst still maintaining production. We investigated the effect of ration formulation on greenhouse gas emissions from high-producing dairy cows by formulating and testing two pelleted concentrate mixes with low-carbon footprint ingredients, compared to a commercial concentrate. One mix was based on domestically sourced ingredients, whereas the other was on available by-products. Both concentrates, when fed in a grass-clover silage diet, reduced the feed-related greenhouse gas emissions without lowering milk yield or increasing the amount of enteric methane produced. We also tested partially replacing the grass-clover-silage in the diet for pregnant dairy heifers with whole-crop wheat silage at 50/50 proportions. Growth rate, feed intake, and enteric methane emissions were comparable between pure grass-clover silage and the whole crop wheat silage mix.

Combining the results of these two feed trials showed that low-carbon footprint concentrate mixes can reduce greenhouse gas emissions at the farm gate. The choice of ingredients, however, can affect the land use in various ways; a by-product-based mix reduced land use, whilst a domestically sourced mix increased it. Similarly, partially replacing silage with whole-crop cereal silage increased emissions but reduced land use. A modelling study of dairy production in Norrland, Sweden, further illustrates these trade-offs. Depending on future consumer values, the scenarios resulted in different outcomes. Intensive systems achieved lower emissions but increased the reliance on feed inputs, whilst net-zero systems required drastic reductions in animal numbers, thereby affecting milk output. More extensive systems reduced the reliance on external feed, but increased milk's carbon footprint. In contrast, local food systems balanced regional milk production with lower emissions and relied less on feed inputs.

The findings highlight that there is no single solution for sustainable dairy farming. Feed rations can make a difference, but the outcomes depend on the prioritized goals, such as emissions, land use, self-sufficiency, or total milk output. Sustainability, therefore, needs to be assessed at several system levels, investigated from the individual animal to the whole region, to capture the complexity and guide informed decisions for the future of dairy production.

Populärvetenskaplig sammanfattning

Klimatförändringarna kräver minskade utsläpp av växthusgaser från alla delar av samhället, inklusive livsmedelsproduktionen. Mjölkproduktionen bidrar med näringsrika livsmedel men utgör samtidigt en betydande källa till utsläpp inom lantbruket. Sektorn har redan gjort framsteg t.ex. genom ökad avkastning per ko och försök med fodertillskott som minskar metan, men fler lösningar behövs.

I den här avhandlingen undersöktes hur foderstater baserade på råvaror med låg klimatpåverkan vid produktionen kan bidra till att minska de totala utsläppen av växthusgaser utan att mjölkproduktionen försämras. Fokus låg på hur fodrets sammansättning påverkar utsläppen från högproducerande mjölkkor, detta genom att ta fram och testa två pelleterade kraftfoderblandningar med lägre klimatavtryck jämfört med ett kommersiellt kraftfoder. Den ena blandningen baserades på inhemskt producerade råvaror (DOM), och den andra på tillgängliga biprodukter (BYP). Båda blandningarna, när de utfodrades tillsammans med gräs-klöverensilage, minskade de foderproduktionsrelaterade växthusgasutsläppen utan att mjölkavkastning eller metanutsläppen från fodersmältningen ökade. I ett annat försök testades att delvis ersätta gräs-klöverensilaget i dräktiga kvigors foderstater med helsädesensilage av vete i förhållandet 50/50. Resultaten visade att tillväxt, foderintag och metanutsläpp från fodersmältningen var likvärdiga mellan de båda kviggrupperna.

Genom att kombinera resultaten från dessa två utfodringsförsök visades att kraftfoderblandningar med lågt klimatavtryck kan minska gårdens växthusgasutsläpp vid gårdsgrinden. Valet av ingredienser påverkar dock markanvändningen på olika sätt: en biproduktbaserad blandning minskade markanvändningen, medan en inhemskt baserad blandning ökade den. På motsvarande sätt ökade delvis ersättning av ensilage med helsädesensilage av vete utsläppen, men minskade markanvändningen. I en modelleringsstudie av framtidens mjölkproduktion i Norrland illustrerades ytterligare dessa avvägningar. Fyra olika scenarier gav olika resultat: intensiva system hade lägre utsläpp men var i högre grad beroende av inköpt foder, medan nettonollsystem i växthusgasutsläpp krävde kraftigt minskat djurantal och därmed lägre mjölkproduktion. Mer extensiva system minskade beroendet av importerat foder men ökade mjölkens klimatavtryck, medan lokala livsmedelssystem kunde upprätthålla regional produktion med lägre utsläpp och minskat beroende av inköpt foder.

Sammantaget visar resultaten att det inte finns någon enskild lösning för en hållbar mjölkproduktion. Foderstater kan göra stor skillnad, men utfallet beror på vilka mål som prioriteras, till exempel minskade utsläpp, markanvändning, självförsörjningsgrad eller total mjölkvolym. Hållbarhet behöver därför bedömas på flera systemnivåer, från den enskilda kon till hela regioner, för att fånga komplexiteten och ge ett bättre beslutsunderlag för framtidens hållbara mjölkproduktion.

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Considering greenhouse gas emissions from feed production in diet formulation for dairy cows as a means of reducing the carbon footprint

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ABSTRACT

Dairy production often faces conflicting goals, such as reducing greenhouse gas emissions, increasing food production and achieving self-sufficiency without transgressing planetary boundaries. This study examined ways to decrease emissions intensity per kg of milk from high-producing cows by selecting feed ingredients with a low carbon footprint while also considering local alternatives. Diets comprising of grass-legume mixture silage and three concentrate mixtures (standard commercial, based on by-products, and domestic crops grown on-farm) were randomly allotted to three groups of high-producing Swedish Holstein cows (N = 48). Over 7 weeks, no differences were observed (mean ± SEM) in feed DM intake (commercial: 24.3, by-products: 24.7, domestic: 24.2 kg/day, ± 0.51 kg/day), energy-corrected milk (**ECM**) yield (commercial: 38.3, by-products: 38.5, domestic: 37.8, ± 0.98 kg/day) or enteric methane production (commercial: 387, by-products: 378, domestic: 402 g/day, ± 17.3 g/day) among the diets. However, an evaluation of the primary carbon footprint of feed production (excluding transportation emissions) showed that the by-products and domestic diets gave lower emissions than the commercial diet, 9.4, 10.2, and 11.9 Feed CO_2 equivalents (**$CO_{2\text{-eq}}$**) kg/day, respectively (SEM: ± 0.38 Feed $CO_{2\text{-eq}}$ kg/day). The emission intensity, expressed as feed emissions per kilogram of ECM yield, showed that the by-product-based and domestic diets generated lower carbon footprints, with emissions of 254 and 284 g Feed $CO_{2\text{-eq}}$/kg ECM, respectively, in comparison to 320 g Feed $CO_{2\text{-eq}}$/kg ECM observed for the commercial diet (SEM: ± 10.7 g Feed $CO_{2\text{-eq}}$/kg ECM). Considering greenhouse gas emissions from feed production in diet formulation resulted in a lower overall feed carbon footprint and lower emission intensity per ECM. These findings can assist in formulating dairy rations for high-yielding dairy cows that balance conflicting goals while maintaining productivity.

Implications

Feed production carbon footprint is an important parameter to consider when formulating dairy rations aiming to improve the environmental sustainability of dairy production. In this study, diets based on by-products reduced feed carbon footprint and emission intensity per kilogram energy–corrected milk both by 21%, while domestically produced feeds resulted in reductions of 14 and 11%, respectively, compared to a commercial mix. Our results contribute to developing sustainable dairy cow feeding strategies by designing rations that optimise productivity, lower carbon footprint, and promote local agricultural production. These findings help distinguish high-producing dairy systems based on their inputs and carbon footprint.

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Introduction

It is generally recognised that approximately 12% of the total anthropogenic greenhouse gas emissions are attributable to livestock production. Ruminant production systems cause the majority of the greenhouse gas emissions from livestock production and consist of enteric CH_4, CO_2 and N_2O (IPCC, 2019). Animal nutrition is a key action target for improved sustainability (FAO, 2023) since feed ration formulation can directly affect animal health, productivity and enteric fermentation. In the coming decades, increases in the global population will increase the demand for food, while the expected improvement in living standards will lead to increased demand for animal-source food (FAO, 2018; Enahoro et al., 2021; van Dijk et al., 2021). These environmental challenges and the risk of exceeding the Earth's biophysical limits (Steffen et al., 2015) create a need to sustainably produce food (Muscat et al., 2021). Different perspectives exist on achieving this (Billen

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et al., 2021). Focusing on the demand perspective has led some to suggest eliminating or reducing the consumption of animal-source foods and switching to a plant-based diet (Poore and Nemecek, 2018; Theurl et al., 2020). From a production perspective, some claim that intensification of production will lower emission intensity, defined as environmental impact per unit of animal-source food produced (Gerber et al., 2011), although this may exacerbate the problem of feed-food competition (Van Zanten et al., 2018). Many have suggested that food production should be prioritised on arable land, while feed production should be considered a secondary priority. Livestock production would then be based on low-opportunity-cost biomass or ecological leftovers (by-products) (Röös et al., 2016; Karlsson et al., 2018b; van Hal et al., 2019; van Selm et al., 2022).

A by-product-based animal-feeding system can address challenges like poor land suitability, feed-food competition, incomplete nutrient cycles and excessive reliance on external inputs (van Zanten et al., 2016; Frehner et al., 2022). It would thus help decrease overall greenhouse gas emissions and increase net food production (Wilkinson, 2011; Patel et al., 2017; Cheng et al., 2022). However, livestock reared in such a system would be subjected to various trade-offs, with adverse effects on productivity that could increase emission intensity. Despite its potential benefits, using by-products as feed has not been sufficiently studied in high-producing dairy cows. One study reported decreased productivity in high-producing dairy cows (Takiya et al., 2019), but most studies have been performed on cows with lower milk production levels (Pang et al., 2018; Karlsson et al., 2019; Guinguina et al., 2021). Furthermore, the global COVID-19 pandemic and the armed conflict in Ukraine affected the agricultural supply chain, creating uncertainty and commodity and labour shortages, resulting in food price volatility and affecting the availability of products (Workie et al., 2020; Lin et al., 2023). This highlights the importance of self-sufficiency and resilience to external shocks. One way to withstand such challenges is to grow most animal feed crops on-farm or have access to other domestically produced feedstuffs.

This study evaluated production responses in high-yielding dairy cows fed concentrates based on by-products or domestically produced feeds, compared with a commercial concentrate. The aim was to address knowledge gaps regarding milk production, enteric CH_4 and associated emissions from feed production. The hypotheses were that (i) feeding a concentrate based on by-products would result in lower milk production and higher CH_4 emissions compared with a commercial concentrate, (ii) using domestically (on-farm) produced ingredients would not impair productivity or result in higher CH_4 emissions compared with a commercial concentrate.

Material and methods

Animals and study design

The study was conducted at the company Lantmännen's experimental dairy farm ''Nötcenter Viken'' in Falköping, Sweden, from May to July 2022. A total of 48 Swedish Holstein cows were used, 15 primiparous and 33 multiparous (mean ± SD; 2.8 ± 1.0 lactations). At the start of the experiment, the cows averaged 185 ± 50 days in milk, with an energy-corrected milk (**ECM**) yield of 43.3 ± 5.32 kg/day and an average BW of 675 ± 54 kg. The cows were divided into two blocks based on parity level, and within each block, cows were randomly assigned to one of three dietary treatments. The treatments consisted of a partial mixed ration composed of grass-legume mixture silage and one of three types of pelleted concentrate: (i) Control (**CON**; a commercial mix (Komplett Maxa 175, Lantmännen Malmö, Sweden), (ii) by-product (**BYP**) and (iii) domestic (**DOM**). The experiment followed a randomised complete block design with the use of a covariate, with 2 weeks of adaptation to the diets and 7 weeks of data collection. Dry matter intake (**DMI**) (mean ± SD, CON: 22.5 ± 2.81, BYP: 22.6 ± 2.47, DOM 22.1 ± 2.72 kg/day), ECM production (CON: 43.5 ± 5.50, BYP: 43.2 ± 5.34, DOM 43.1 ± 5.49 kg/day) and BW (CON: 690 ± 49.8, BYP: 669 ± 57.4, DOM 671 ± 54.2 kg/day) were collected the week before the start of the experiment and were used as covariate data in the statistical analysis.

The cows were housed in a free-stall pen with sufficient cubicles covered with rubber mats and peat as bedding material. The cows had *ad libitum* access to their allocated partial mixed ration, salt licks, and water. A unique radio-frequency ear tag facilitated individual cows' identification, enabling automatic recognition in the feeding stations, BW scale (at the start and end of the experiment), milking unit, and the unit for enteric CH_4 emissions recording. The cows were milked voluntarily in a free cow traffic single-station voluntary milking system (310TM system; DeLaval International AB, Tumba, Sweden). Individual daily feed intake was recorded automatically using feed mangers on scales (BioControl, CRFI, Rakkestad, Norway). A single GreenFeed system unit (C-Lock Inc., Rapid City, SD, USA) was used for continuous measurements of emissions of enteric CH_4, respiratory CO_2 and O_2.

Dietary treatments

The dietary treatments (silage and concentrate pellets) were optimised using NorFor – the Nordic feed evaluation system (2011) to support a dairy cow producing 45 kg ECM per day. The silage-to-concentrate ratio was set at 45:55 on a DM basis for all rations. The rations were formulated to be as similar as possible, with prioritisation in descending order based on net energy, CP, starch, fat and NDF content (Table 1). The chemical composition of the ingredients used during ration formulation is presented in Supplementary Table S1.

All cows received the same silage, consisting of a grass-legume mixture, from the first cut of multiyear leys. The silage was a mixture of timothy (Phleum pratense L.), meadow fescue (Festuca pratensis L.) and perennial ryegrass (Lolium pratense L.) with less than 25% of red clover (Trifolium pratense L.) and white clover (Trifolium repens L.). The primary difference between treatments lay in the type of pelleted concentrate feed included in the dairy rations. The CON group was fed a commercially available pelleted concentrate mix (Komplett Maxa 175, Lantmännen Malmö, Sweden) chosen to represent a typical pelleted concentrate used by high-producing Swedish dairy herds (Lantmännen communication). For the BYP concentrate, ingredients were selected from by −products available in sufficient quantities in the Swedish market, either through domestic production or international trade. Priority was given to cereal by-products (e.g., wheat middlings), which were included at a minimum level of 40% of DM concentrate, and cereals were added to achieve a minimum of 170 g of starch per kg of DMI. For the DOM concentrate, ingredients were limited to those that could be supplied through domestic production, such as cereals, oilseed by-products, sugar by-products, and legume grains. During the formulation of the BYP and DOM concentrates, each ingredient's carbon footprint was taken into account, incorporating emissions in the form of fossil CO_2, N_2O and excluding land-use change. The carbon footprint was expressed as CO_2 equivalents (**$CO_{2\text{-eq}}$**) and was sourced in descending priority order from country-specific datasets, international datasets, and scientific publications (Garcia-Launay et al., 2014; GFLI, 2019; Lindberg et al., 2021; RKFS, 2021; Supplementary Table S2). All concentrates were pelleted by Lantmännen Lantbruk AB (Malmö, Sweden) (Table 2). The pelleting process (3.8 mm pellet) included milling,

Table 1
Chemical composition (mean ± SD; g/kg DM unless otherwise stated) of silage, control, by-product-based and domestic concentrates and of sugarbeet pulp pellets.

Item	Silage	CON	BYP	DOM	Betfor®
DM (g/kg)	275 ± 11.4	902 ± 3.7	903 ± 4.6	902 ± 2.9	925 ± 3.1
Ash	90.1 ± 2.70	67.4 ± 1.58	71.3 ± 2.16	75.6 ± 1.10	72.9 ± 0.98
CP	175 ± 5.8	178 ± 1.1	185 ± 1.4	181 ± 1.9	87.1 ± 1.35
aNDFom	488 ± 7.2	166 ± 9.3	241 ± 11.6	199 ± 7.2	348 ± 4.7
iNDF	54.5 ± 2.46	43.5 ± 2.69	66.6 ± 2.66	46.8 ± 0.50	27.2
Starch	NA	360 ± 3.8	300 ± 14.3	311 ± 5.8	15.8 ± 4.47
Ether extract	37.8 ± 1.67	54.8 ± 0.23	41.2 ± 0.57	44.4 ± 0.91	5.37 ± 0.018
IVOS (%)	88.7 ± 0.79	NA	NA	NA	NA
NEL (MJ/kg DM)	6.75[†]	7.36[†]	6.68[†]	7.05[†]	6.39[†]

Abbreviations: CON = Control mix; BYP = By-product based mix; DOM = Domestically produced mix; Betfor = Sugarbeet pulp pellets; aNDFom = amylase NDF organic matter; iNDF = indigestible NDF; IVOS = Ruminal fluid digestible organic matter; NA: Not analysed; NEL = Net energy for lactation.
[†] Based on the chemical composition according to NorFor (2011).

blending and heat treatment according to European and Swedish feed regulations (EC, 2005; SJVFS, 2018).

During the trial, the silage was mixed with the respective concentrate into three different partial mixed rations using a stationary mixer (Feed Mixer-Multimix, Cormall, Sønderborg, Denmark) and provided once daily *ad libitum* via an automatic feeding wagon (Free Stall Feeder M2000 XL, GEA, Düsseldorf, Germany). Silage DM content was determined twice per week throughout the experiment to adjust the composition of the partial mixed ration as needed. Additionally, cows received approximately 2 kg of concentrate (CON, BYP or DOM) per milking in the voluntary milking system (average 3.1 milking occasions per day), and sugar beet pellets (Betfor®, Nordic Sugar AB, Malmö, Sweden) were offered as attractant feed in the GreenFeed unit. These feedstuffs were included in the DMI calculation presented in Table 3.

Sample collection and analyses

Feed

During milk and faeces sampling weeks (1, 4 and 7), silage and concentrate samples were collected four times per week (Monday to Thursday). In other weeks, silage samples were collected five times per week (Monday to Friday), while concentrate samples were collected twice weekly (Monday and Thursday). All samples were stored at −20 °C until analysis. At the end of each week, frozen silage and concentrate samples were pooled per treatment and

Table 2
Composition (% of fresh matter) and estimated carbon footprint of silage, control, by-product-based, and domestic concentrate feeds used in the experiment with Swedish Holstein cows.

	Feed				
Ingredient	Silage	CON	BYP	DOM	CF ($CO_{2\text{-eq}}$ g/kg)[1]
Oat hulls	–	–	1.2	–	89[††]
Wheat bran	–	4.0	–	–	89[††]
Distillers' grain[2]	–	–	10.0	–	214[††]
Wheat middlings	–	–	41.1	–	289[††††]
Field beans	–	–	–	11.5	336[††††]
Barley	–	18.4	28.0	36.5	361[††††]
Molasses	–	2.5	3.0	3.0	370[††]
Grass-legume mixture silage	100	–	–	–	390[†]
Oats	–	–	3.0	8.5	390[††††]
Wheat	–	8.0	–	–	400[††]
Heat-treated rapeseed meal[3]	–	20.0	6.0	15.5	460[††††]
Dried sugar beet pulp (unmolassed)	–	6.6	2.0	15.0	460[††]
Rapeseed meal	–	5.3	–	–	506[††††]
Rapeseed cake	–	3.0	–	–	493[††††]
Maize	–	25.3	–	–	605[††††]
Crushed rapeseeds	–	–	2.0	5.6	917[††††]
Vegetable fats					
AkoFeed® Gigant75	–	2.8	–	–	1 000[††]
AkoFeed® Cattle	–	0.5	–	–	2 300[††]
Rumen-protected amino acids					
MetaSmartDry	–	0.2	–	–	3 000[†††]
LysiGEM BB	–	0.1	–	–	4 300[†††]
Minerals[4]	–	3.3	3.7	4.4	42[††] - 1 168[††††]
Pellet CF ($CO_{2\text{-eq}}$ g/kg)[5]		525	338	425	

Abbreviations: CON = Control mix; BYP = By-product based mix; DOM = Domestically produced mix; $CO_{2\text{-eq}}$ = Carbon dioxide equivalent; CF = Primary estimated carbon footprint.
[1] Primary carbon footprint expressed as $CO_{2\text{-eq}}$ g/kg fresh matter, except for Grass-legume mixture silage, which is expressed as $CO_{2\text{-eq}}$ g/kg DM.
[2] Fibre and yeast cells from ethanol manufacturing (Agrow Drank 90, Lantmännen Agroetanol, Norrköping, Sweden).
[3] Solvent-extracted and heat-moisture-treated rapeseed meal (ExPro®, AAK Sweden AB, Karlshamn, Sweden).
[4] Containing minerals, vitamins and trace elements. The values in the table describe the variation in $CO_{2\text{-eq}}$ among all included ingredients within this category; however, as these are small added quantities, they do not significantly impact the overall results.
[5] Primary carbon footprint expressed as g $CO_{2\text{-eq}}$ per kg product.
[†] Source: Lindberg et al. (2021).
[††] Source: Lantmännen's estimated value based on RKFS (2021) for calculating the carbon footprint of feeds.
[†††] Source: Synthetic amino acids impact based on Garcia-Launay et al. (2014).
[††††] Source: GFLI dataset (2019).

Table 3
Effect of the control, by-product-based and domestic dietary treatments assessed across the entire experimental period on feed intake, daily milk yield, milk yield-to-feed intake ratio and BW in Swedish Holstein cows.

Item	Diet			SEM[1]	*P*-value
	CON	BYP	DOM		
Number of cows	16	15	15		
DMI (kg/day)	24.3	24.7	24.2	0.51	0.707
Silage DMI (kg/day)	10.6	11.0	10.5	0.50	0.701
Concentrate DMI (kg/ day)[†]	13.4	13.2	12.9	0.43	0.650
Silage/DMI (%)	43.7	44.9	44.7	0.78	0.437
Milk yield (kg/ day)[†]	39.6[a]	36.0[b]	38.7[ab]	0.97	0.017
Milk yield/DMI[†]	1.62	1.48	1.59	0.054	0.103
BW (kg)	697	680	688	5.7	0.071

Abbreviations: CON = Silage plus control mix; BYP = Silage plus by-product based mix; DOM = Silage plus domestically produced mix; DMI = DM intake.
[†] Significant effect of days in milk.
[1] Greatest SEM value obtained.
[a,b] Values within a row with different superscripts differ significantly at $P < 0.05$ after adjustment for multiple testing using Tukey's procedure.

week. All analyses were performed by the laboratory at the Department of Applied Animal Science and Welfare, Swedish University of Agricultural Sciences, Uppsala, Sweden. The DM content of the silage was determined by a two-step procedure according to Åkerlind et al. (2011), first drying at 60 °C overnight and milling and then drying at 103 °C for 16 h overnight. The DM content of the concentrates was determined by drying at 103 °C for 16 h (Jennische and Larsson, 1990). Ash content for all feeds was determined by ignition at 550 °C for three hours (Jennische and Larsson, 1990). The other analyses were performed on samples dried at 60 °C for 16–20 h and allowed to stabilise for at least 4 h at room temperature. CP was analysed using an automated Kjeldahl procedure (Foss, Hillerød, Denmark; Nordic Committee on Food Analysis, 1976). The concentrates were analysed enzymatically for starch (including maltodextrin) according to Larsson and Bengtsson (1983). All feeds were analysed for amylase NDF organic matter (**aNDFom**) according to Chai and Udén (1998) and indigestible NDF (**iNDF**) according to Åkerlind et al. (2011). The pelleted feeds were pooled for ether extract analysis according to the batch delivered to the farm. The CON and sugar beet pulp pellets were composited in one sample each for the entire experiment, while for DOM and BYP, two samples were composited per feed by pooling weeks 1–4 and weeks 5–7. Silage and pelleted feed samples were analysed for ether extract according to European Commission regulations (EC, 2009). The silage samples were also analysed for *in vitro* organic matter digestibility (**OMD**). The net energy for lactation content in the concentrates and silage was calculated according to the NorFor system (Volden and Nielsen, 2011).

Milk

Milk yield was recorded automatically at each milking for all cows throughout the experiment, and the data were retrieved from the DelPro (DeLaval International AB, Tumba, Sweden) system. Milk samples were collected over two consecutive 24-hour periods one week before the adaptation period (used as a covariate) and then again during weeks 1, 4 and 7. Samples were collected automatically from the milking unit into 20-mL tubes containing bromo-2-nitropropane-1.3-diol on every milking occasion and stored at +4°C until analysis (performed within 7 days). Milk samples were analysed for concentrations of milk fat, milk protein, milk urea nitrogen (**MUN**), lactose and somatic cell count using IR Fourier-transform spectroscopy (CombiScope FTIR 300 HP, Delta Instruments B.V., Drachten, the Netherlands). Lactose was corrected for lactase monohydrate by dividing by 1.053. Due to the irregular milking intervals that occur in automatic milking, individual milk production per cow and day was calculated according to Nielsen et al. (2010). During week 4, due to a delayed changing of the sampling cassette, nine tubes were filled with milk samples from two animals, and these tubes were thus discarded. Energy-corrected milk yield was calculated based on fat, protein and lactose content according to Sjaunja et al. (1990):

$$ECM\,(kg) = Milk\ yield\,(kg) \times \left(\frac{38.3 \times fat\left(\frac{g}{kg}\right) + 24.2 \times protein\left(\frac{g}{kg}\right) + 16.54 \times lactose\left(\frac{g}{kg}\right) + 20.7}{3140}\right)$$

Faeces and digestibility

Faecal grab (~400 g) samples were collected from the rectum of each cow once daily on three consecutive days (Tuesday to Thursday) in weeks 1, 4 and 7 (Mehtiö et al., 2016). These samples were pooled per cow and week, stored at −20 °C until required, thawed, subsampled, subjected to freeze-drying, milled and analysed for DM, ash, CP, NDF and iNDF. The total amount of faeces was estimated from the total intake of iNDF and the content of iNDF in the faeces. For the iNDF analysis, composite faeces samples were freeze-dried, milled and analysed according to Åkerlind et al. (2011). Total-tract apparent digestibility was calculated from the estimated feed intake, faecal excretion and their chemical composition:

$$\text{Apparent total tract digestibility} = \frac{\text{Feed intake} - \text{Faecal output}}{\text{Feed intake}}$$

The calculation was based on data from the corresponding days of each sampling week.

Enteric gas emissions

Exhaled gases (O_2, CO_2, CH_4) were measured individually using a GreenFeed system unit (C-Lock Inc.; Zimmerman et al., 2011) throughout the whole experiment (weeks 1–7). The unit was equipped with a head position sensor, and data were excluded when head position criteria were unmet. All animals could visit the GreenFeed unit voluntarily, with a minimum interval of five hours between visits (maximum five visits/day). A sugar beet pulp-based pelleted bait was used to attract cows and maintain correct head positioning, dispensed at 30 g per cup drop, with up to 8 drops per visit and with 1 cup drop per 40 s. Gas emissions were calculated by subtracting background concentrations from those recorded during each visit and adjusting for airflow, temperature, and pressure using the ideal gas law. GreenFeed used a non −dispersive near-IR analyser to measure CH_4, O_2, and CO_2, calibrated every third day with standard gases provided by C-Lock Inc. to account for signal drift. Monthly recovery tests using known

CO_2 amounts confirmed an average recovery rate of 99.5%, and flow coefficients were adjusted accordingly (C-Lock Inc.). The calibration and recovery process were performed based on the manufacturer's recommendations (https://greenfeed.c-lockinc.com). Data were uploaded every 24 h through a web-based system (C-Lock Inc.), and the validated data were used for the statistical analysis.

Data management and statistical analysis

All data were analysed in R Studio (Posit Team, 2022; R Core Team, 2022) using basic R commands and the packages tidyverse (Wickham et al., 2019) and ggplot2 (Wickham, 2016). During the experimental period, two cows were excluded due to health issues unrelated to the experiment. One cow from the DOM treatment group suffered a mouth injury, while another from the BYP group developed pneumonia. Furthermore, one cow from the BYP group lost her ear identification tag during the experiment, resulting in abnormal feed intake values and milk and ECM values. The animal was identified as an outlier during the statistical analysis, and milk composition values and ECM values were removed from the dataset. Additionally, due to an error, one cow from the CON group had access to the wrong diet for 24 h during the experiment, and thus, her feed intake values were removed for that day. A successful visit to the GreenFeed was defined as a visit event with a duration of at least three minutes. A cut-off value of 20 successful visit events per animal during the entire experiment was used to ensure reliable data (Manafiazar et al., 2016). Animals with a lower number of successful visits were removed from the dataset. This resulted in 24 remaining animals (nine CON (three primiparous, six multiparous), six BYP (three primiparous, three multiparous) and nine DOM (three primiparous, six multiparous)). This resulted in a total of 1 494 successful visits for the entire experiment and an unbalanced design, with 679, 277 and 538 successful visits for the CON, BYP and DOM groups, respectively.

Data were averaged by cow and week, and a linear mixed-effects model with a continuous AR(1) correlation structure "corCAR1" was fitted for each response variable using the "nlme: Linear and Nonlinear Mixed Effects Models" package (Pinheiro et al., 2022). ANOVA was performed using the "car: Companion to Applied Regression" package (Fox and Weisberg, 2019) with the options type III option and Kenward-Roger approximation method. Treatment, week, and parity groups were used as fixed effects, while animal was used as a random effect to account for repeated measurements. A statistical model with the variables days in milk as a covariate to account for different stages of lactation, two-way interactions (treatment × week and treatment × parity group) and three-way interactions (treatment × week × days in milk) was tested, and explanatory variables were removed from the model if non-significant. Average milk yield, ECM yield, DMI and BW in the week before the adaptation period were included as covariates for milk, ECM yield, DMI, and BW, respectively. All residuals were tested for normality, and log transformation was performed if needed for the statistical analysis (stated in the following results tables where relevant). Statistical significance was set at $P < 0.05$, and pairwise comparisons adjusted using Tukey's method were performed using the means package (Lenth, 2023).

Results

There were no differences in total feed intake or intake of concentrates and silage between cows in the CON, BYP and DOM treatments. Milk yield differed between treatments throughout the entire experimental period. Cows on the BYP treatment produced 9% less milk compared to those on the CON treatment, while the DOM treatment group did not differ from either (Tables 3 and 4). On milk sampling days, no differences were observed between the treatments in milk yield, ECM yield, milk protein, lactose and somatic cell count. Milk fat content from cows on the BYP treatment was 8% higher compared to those on the CON treatment. However, MUN was 19% higher for BYP and 12% higher for DOM compared to CON. No treatment × week interaction was observed for any parameters reported in Tables 3 and 4.

Enteric CH_4 emissions, respiratory CO_2 and feed primary $CO_{2\text{-eq}}$ are presented in Table 5. There were no differences between the treatments in enteric CH_4 production or the CH_4 emissions intensity. Feed primary $CO_{2\text{-eq}}$ expressed as g/day differed between the treatments, as planned. Animals receiving the BYP and DOM diets had 21 and 14% lower Feed primary $CO_{2\text{-eq}}$ than those receiving CON. Feed primary $CO_{2\text{-eq}}$ expressed in g/kg milk was 15% lower in BYP cows compared with CON cows, while feed primary $CO_{2\text{-eq}}$ expressed as g/kg ECM was 21 and 11% lower in cows on the BYP and DOM diets, respectively, compared with those on the CON diet (Table 5). No treatment × week interaction was observed for any of the parameters reported in Table 5.

Intake and apparent digestibility results per treatment are presented in Table 6. Intake of aNDFom was 16% higher in BYP than in CON cows, whereas DOM cows did not differ from those in the other two treatments. Similarly, iNDF intake was 27% higher in BYP compared with CON cows, while no difference was observed between DOM and CON cows. Starch intake was 18% lower in BYP and 16% lower in DOM cows than in CON cows, while ether extract intake was 14% lower for BYP and DOM cows compared to CON cows. A treatment × week interaction ($P < 0.001$) was observed for iNDF and starch intake; however, posthoc comparisons suggest these changes were not consistently large or statistically distinct at each week (Supplementary Figs. S1 and S2). Animals consuming the BYP and DOM diet had consistently lower starch intake values and higher iNDF intake values throughout the experiment (weeks 1–7) than CON while no difference was observed between BYP and DOM.

DM and apparent OMD were lower by 3.5 percentage units in BYP cows compared with the other two diets, while no difference was observed between CON and DOM cows. The apparent digestibility of aNDFom differed between all treatments, with BYP cows having the lowest value (3.5 percentage units decrease compared to CON) and DOM cows the highest (2.9 percentage units increase compared to CON). A treatment × week interaction was observed for the apparent digestibility of DM, organic matter and aNDFom (Supplementary Table S3). Specifically, for the BYP group, DM digestibility was lower during weeks 1 and 7 compared to CON, but no difference was observed during week 4. Digestibility of organic matter was lower for animals that received BYP compared to CON throughout weeks 1, 4 and 7. Digestibility of aNDFom was lower for animals receiving BYP compared to CON throughout weeks 1 and 7, but no difference was observed during week 4. Animals in DOM had higher aNDFom digestibility during week 4 compared to CON, while no difference was observed between weeks 1 and 7.

Discussion

Intake and digestibility

No differences in DMI were found between the diets, for either concentrate or silage, aligning with findings from previous studies comparing by-product-based and cereal-based diets (Karlsson et al., 2018a; Guinguina et al., 2021). In a previous comparison of conventional and by-product-based diets, Takiya et al. (2019)

Table 4
Effect of the control, by-product-based and domestic dietary treatments assessed on sampling days during weeks 1, 4 and 7 on daily milk yield, energy-corrected milk yield, milk components and the ratio of milk yield and energy-corrected milk yield to DM intake in Swedish Holstein cows.

Item	Diet			SEM[1]	*P*-value
	CON	BYP	DOM		
Number of cows	16	14	15		
DMI (kg/day)	24.3	24.6	24.1	0.45	0.678
Milk yield (kg/day)	39.5	37.1	38.5	0.977	0.188
ECM (kg/day)	38.3	38.5	37.3	0.988	0.635
Fat (%)[†]	3.97[b]	4.29[a]	4.01[b]	0.078	0.004
Fat yield (kg/day)	1.53	1.57	1.50	0.039	0.323
Protein (%)[†]	3.42	3.45	3.36	0.036	0.143
Protein yield (kg/day)	1.31	1.28	1.25	0.037	0.484
Lactose (%)	4.56	4.62	4.63	0.032	0.208
Lactose yield (kg/day)[†]	1.78	1.70	1.75	0.052	0.500
Milk urea N (mg/100 mL)	12.0[b]	14.2[a]	13.4[a]	0.260	<0.001
Somatic cell count (1 000/ml)[††]	87.5	137.5	86.5	34.7	0.205
ECM/DMI	1.59	1.58	1.55	0.050	0.806

Abbreviations: CON = Silage plus control mix; BYP = Silage plus by-product based mix; DOM = Silage plus domestically produced mix; DMI = DM intake; ECM = Energy −corrected milk.
[†] Significant effect of days in milk.
[††] Back-transformed from log-transformed values (antilog scale) for interpretability.
[1] Greatest SEM value obtained.
[a,b] Values within a row with different superscripts differ significantly at $P < 0.05$ after adjustment for multiple testing using Tukey's procedure.

Table 5
Effect of control, by-product-based and domestic concentrate diets on enteric gas emissions and feed primary carbon footprint in Swedish Holstein cows.

Item	Diet			SEM[1]	*P*-value
	CON	BYP	DOM		
Number of cows	9	6	9		
Successful visits per animal[2]	75 ± 35	46 ± 25	60 ± 20		
DMI (kg/day)[3]	24.4	24.5	24.2	0.49	0.885
Enteric CH_4 (g/day)	387	378	402	17.3	0.500
CH_4/Milk (g/kg)[4 ††]	10.39	9.98	11.43	0.797	0.351
CH_4/ECM (g/kg)	10.83	9.82	11.57	0.814	0.241
CH_4/DMI (g/kg)	16.4	15.8	17.3	0.60	0.119
Exhaled CO_2 (g/day)	12 941	13 042	13 070	396.0	0.954
CO_2/Milk (g/kg)[4 † ††]	351	358	368	28.1	0.858
CO_2/ECM (g/kg)	363	340	377	28.8	0.599
CO_2/DMI (g/kg)	552	548	564	19.0	0.762
CH_4/CO_2 (g/kg)[†]	29.8	28.6	30.9	0.75	0.048
Number of cows	16	15	15		
Feed primary $CO_{2\text{-eq}}$ (g/day)[††]	11 907[a]	9 423[b]	10 191[b]	378.0	<0.001
Feed primary $CO_{2\text{-eq}}$ /Milk (g/kg) [2 † ††]	311[a]	264[b]	279[ab]	10.8	0.004
Number of cows	16	14	15		
Feed primary $CO_{2\text{-eq}}$ /ECM (g/kg)	320[a]	254[b]	284[b]	10.7	<0.001

Abbreviations: CON = Silage plus control mix; BYP = Silage plus by-product based mix; DOM = Silage plus domestically produced mix; DMI = DM intake; ECM = Energy −corrected milk; $CO_{2\text{-eq}}$ = Carbon dioxide equivalent.
[†] Significant effect of days in milk.
[††] Back-transformed from log-transformed values (antilog scale) for interpretability.
[1] Greatest SEM value obtained.
[2] Total number of successful visits per cow during the entire experiment (weeks 1–7).
[3] DM intake used in methane and carbon dioxide yield calculations.
[4] Milk yield during the entire experimental period.
[a,b] Values within a row with different superscripts differ significantly at $P < 0.05$ after adjustment for multiple testing using Tukey's procedure.

found no effect of diet on DMI in Holstein dairy cows postpeak lactation (150 days in milk). However, a decrease in DMI was observed in cows fed the by-product-based diet during late lactation (231 days in milk). In our study, the apparent total tract digestibility of DM, organic matter and aNDFom differed between the CON, BYP and DOM diets, where the BYP treatment group showed reduced digestibility of all the mentioned parameters. By-products, in general, vary in chemical composition, and by-products used in ruminant diets may, at large, be based on fibrous feeds or legume crops (Halmemies-Beauchet-Filleau et al., 2018). The BYP diet resulted in a higher intake of iNDF compared to CON and DOM, which could explain the lower digestibility of DM, OM, and aNDFom observed in BYP compared to CON and DOM. Similarly, Guinguina et al. (2021) observed decreases in DM, organic matter and NDF digestibility and no treatment effect on CP digestibility for diets based on sugar beet pulp, wheat middlings, barley fibre and wheat bran compared with cereal-based diets. Also, Karlsson et al. (2018a) observed decreased OMD for by-product-based diets composed mainly of sugar beet fibre, dried distillers' grains with solubles and rapeseed meal, compared to a cereal-based diet.

The similar DMI and OMD levels observed between CON and DOM indicate that domestically produced ingredients such as cereals and field beans can successfully replace maize kernels and heat-treated rapeseed meal without a negative response in performance. This finding is in agreement with previous studies that

Table 6
Effect of control, by-product-based and domestic concentrate diets on intake and apparent total-tract digestibility in Swedish Holstein cows.

Item	Diet			SEM[1]	*P*-value
	CON	BYP	DOM		
Number of cows	16	15	15		
Intake					
Organic matter (kg/day)	22.1	22.5	21.5	0.08	0.605
aNDFom (kg/day)[††]	7.41[b]	8.58[a]	7.69[ab]	0.309	0.006
iNDF (kg/day)	1.16[b]	1.47[a]	1.16[b]	0.045	<0.001
CP (kg/day)	4.19	4.38	4.12	0.153	0.447
RDP (kg/d)[†† †††]	2.80[b]	3.29[a]	2.97[b]	0.094	<0.001
Starch (kg/day)[†]	4.62[a]	3.81[b]	3.87[b]	0.131	<0.001
Ether extract (kg/day)	1.11[a]	0.95[b]	0.95[b]	0.035	<0.001
Net energy lactation (MJ/day)[††††]	174	168	165	5.12	0.371
Net energy balance (%)[††††]	102.2	100.3	99.6	2.54	0.718
Apparent digestibility (%)					
DM	66.8[a]	63.3[b]	66.7[a]	0.61	<0.001
Organic matter	68.2[a]	64.7[b]	68.2[a]	0.58	<0.001
aNDFom	60.0[b]	56.5[c]	62.9[a]	0.75	<0.001
CP	59.4	59.2	60.1	0.84	0.699

Abbreviations: CON = Silage plus control mix; BYP = Silage plus by-product based mix; DOM = Silage plus domestically produced mix; aNDFom = amylase NDF organic matter; iNDF = indigestible NDF; RDP = Rumen degradable protein.
[†] Significant effect of days in milk.
[††] Back-transformed from log-transformed values (antilog scale) for interpretability.
[†††] Calculated in IndividRAM software (Växa, 2008), according to NorFor (2011), based on feed intake and dairy ration composition during the entire experiment (weeks 1–7).
[††††] Calculated in IndividRAM software (Växa, 2008), according to NorFor (2011), based on feed intake, dairy ration composition and energy-corrected milk production on weeks 1, 4 and 7.
[1] Greatest SEM value obtained.
[a,b,c] Values within a row with different superscripts differ significantly at $P < 0.05$ after adjustment for multiple testing using Tukey's procedure.

investigated the effect of replacing rapeseed meal (Räisänen et al., 2023) or soybean meal (Cherif et al., 2018; Johnston et al., 2019) with field beans. The higher aNDFom digestibility in DOM could result from the higher inclusion of ingredients with high content of potentially degradable NDF, such as sugarbeet pulp and barley (NorFor, 2011). Milk production

Milk yield measured during the entire experiment was lower for the cows receiving the BYP diet compared with CON cows, while no differences were observed for the DOM group compared with the other two groups. The pattern was similar on sampling days, with the lowest numerical yield observed in the BYP group, but no statistical difference was observed between the treatments. Both parameters are presented to maintain transparency and inform about the milk yield on the specific days selected for sampling and analysis of milk composition. The difference in milk production during the entire experiment can be attributed to the lower OMD observed in BYP compared to CON and DOM, since DMI levels were similar between treatments. Incorporating by-products in dairy cow diets poses challenges due to variations in the chemical composition of available by-products, leading to inconsistent effects on DMI and milk yield (Pang et al., 2018; Takiya et al., 2019; Guinguina et al., 2021). This variation was evident in this study's larger SD values for BYP concentrate composition. The higher milk fat content in the BYP group compared to the CON group can be attributed to the higher aNDFom intake, which acts as a lipogenic nutrient (Van Knegsel et al., 2007). Other feed trials examining the production response of dairy cows in mid to late lactation have reported similar effects of by-product-based versus cereal-based concentrates on production performance. For instance, Ertl et al. (2016) replaced cereal grains and pulses with a mixture of wheat bran and sugar beet pulp without any adverse effects on ECM yield or milk composition. Karlsson et al. (2018a) observed no adverse effects on ECM yield but higher milk fat content when cereal grains and soybean meal were substituted by a combination of sugar beet pulp, dried distillers' grains with solubles, and rapeseed meal. Guinguina et al. (2021) replaced cereal-based concentrates with by-product-based diets for dairy cows in early lactation, observing no reductions in milk yield or alterations in milk composition.

Milk protein content and milk protein yields were similar among treatments. However, MUN levels were higher for animals in BYP and DOM compared to CON. Dietary CP content is the primary nutritional factor influencing MUN (Nousiainen et al., 2004) and did not differ among diets. The increased MUN levels could, thus, indicate differences in protein quality among treatments. Higher amounts of soluble CP and higher CP degradation rates in the rumen are expected to impact the ability of rumen microbes to fully utilise the produced ammonia (Hof et al., 1997; Nocek and Russell, 1988). The main protein source in the CON concentrate pellet was heat-treated rapeseed meal, which resulted in the lowest MUN values. On the contrary, BYP and DOM concentrate pellets consisted mainly of ingredients with high levels of rapidly available CP and high overall ruminal CP availability. Specifically, based on their CP content and inclusion levels, wheat middlings and barley constitute approximately 60% of BYP concentrate CP content. The difference in MUN levels between CON and BYP can thus be attributed to the higher intake of rumen-degradable protein by the BYP group. Field beans and barley constitute approximately 45% of the DOM concentrate CP, partially replacing the heat-treated rapeseed meal in the DOM pelleted concentrate. Compared with CON, the increased MUN levels in the DOM group agree with previous studies' findings, where field beans replaced rapeseed expeller (Räisänen et al., 2023). Furthermore, Puhakka et al. (2016) found that MUN levels tend to increase as rapeseed meal is replaced by field beans on dairy rations with high CP levels. Despite the differences between the treatments, MUN levels from CON and DOM cows were within the acceptable range (9.0–14.0 mg/100 ml) identified by Sawa et al. (2011), while BYP cows had slightly higher levels. Increased MUN levels could indicate decreased protein use efficiency and higher urinary nitrogen excretion.

Greenhouse gas emissions

Feeding the different concentrate mixtures did not result in differences in CH_4 production (g/day), yield (g/kg DMI), or intensity (g/kg milk or ECM) despite the lower milk yield in the BYP group. This agrees with previous findings of no difference in CH_4 production, yield or intensity between cereal-based and by-product-based diets with similar ingredients as the one used in the current experiment containing sugar beet pulp, wheat bran, rapeseed meal, dried distillers' grains with solubles, palm kernel expeller and molasses (Pang et al., 2018). The replacement of soybean meal with field beans in dairy rations has also resulted in no differences in CH_4 production, yield or intensity (Cherif et al., 2018; Johnston et al., 2019). In contrast to our results, Guinguina et al. (2021) reported decreased CH_4 production (g/d) and a lower amount of CH_4 yield (g/kg DMI) for grass-legume mixture silage-based diets containing unmolassed beet pulp, wheat middlings, barley fibre and wheat fibre compared with diets containing barley, oat and wheat grains.

Production of enteric CH_4 is mainly correlated with DMI (Mills et al., 2003; Yan et al., 2006; Ramin and Huhtanen, 2013; Beauchemin et al., 2022). The similar levels of CH_4 production observed for the CON, BYP and DOM diets were mainly due to the lack of differences in DMI between cows in these treatments. Other dietary parameters, such as OMD and NDF, fatty acid and CP intake (Nielsen et al., 2013; Niu et al., 2021; Donadia et al., 2023), as well as animal parameters such as BW and milk yield (Yan et al., 2006; Donadia et al., 2023), also influence CH_4 yield. No difference was observed in enteric CH_4 production or yield despite the difference in OMD and intakes of NDF and ether extract among treatments. The enteric CH_4 emissions were comparatively low in terms of production, yield and intensity relative to other studies (Pang et al.,2018; Karlsson et al., 2019; Guinguina et al., 2021). This outcome may be attributed to the higher observed DMI, the lower observed apparent total tract digestibility, the inferred faster passage rate and differences in the dietary fat content (Patra, 2013). Furthermore, the forage inclusion was lower in this experiment (45%) compared to the aforementioned studies (59–62%), which could also explain the lower enteric CH_4 production (Aguerre et al., 2011).

The higher aNDFom in the BYP group and the lower starch and ether extract intake in the BYP and DOM group did not affect CH_4 yield. However, higher CH_4 yield values in the BYP and DOM group may have been expected, at least because of the lower starch concentration, since rapidly fermentable starch increases propionate production. Propionate production serves as an alternative metabolic hydrogen sink to methanogenesis (Nielsen et al., 2013; Niu et al., 2021; Beauchemin et al., 2022). In the present study, the ether extract concentration was below 5% in all diets, and the difference between the diets was not large enough to result in a significant effect on CH_4 production. The lack of treatment effect on the CH_4/CO_2 ratio indicates no difference in the efficiency of microbial fermentation of the feed or metabolisable energy utilisation (Madsen et al., 2010).

Increased dietary inclusion of vegetable oils is often proposed as an enteric CH_4 mitigation strategy (Nielsen et al., 2013; Niu et al., 2021; Beauchemin et al., 2022; Donadia et al., 2023); however, their efficacy is influenced by several factors such as source, quantity, degree of saturation and carbon chain length of the fatty acids (Beauchemin et al., 2022). Vegetable oils rich in C16:0, such as those in the CON diet, are commonly included in dairy cow rations to enhance milk fat production. However, these vegetable oils are mainly derived from palm or palm kernel, leading to long transport distances and a high carbon footprint (GFLI, 2019; RKFS, 2021). This raises concerns about potential trade-offs, including natural habitats, peatland drainage, biodiversity loss and increased risk of forest fires (Meijaard et al., 2020). To address these challenges, the BYP and DOM diets used crushed rapeseed, which has a lower carbon footprint per kilogram and can be sourced domestically or from other European countries. In this study, ECM yield and CH_4 production were similar across treatments, while BYP and DOM had lower Feed $CO_{2\text{-eq}}$ values. This suggests that using vegetable fat in dairy rations involves uncertainties and trade-offs, and their production benefits must be weighed against their carbon footprint. Selecting fat sources with a lower carbon footprint and shorter supply chains could be one step towards more sustainable dairy production.

A significant practical challenge faced during this study was the reluctance of the animals to visit the GreenFeed unit. A plausible explanation is that the animals received up to 7 kg/day of concentrate feed from the automatic milking station, so the maximum intake of pellets from the GreenFeed unit (1 200 g/day) may have been insufficient attraction (mean pellet DMI per animal 363 g/d). We compensated for the reluctance of the animals to visit the unit by using a cut-off point of 20 successful visits per animal. The use of a low cut-off point might have resulted in increased residual variance for daily CH_4 for the animals with fewer visits (Arthur et al., 2017; Dressler et al., 2023), but allowed us to consider more data points in our analysis. Using a cut-off point of 30 successful visits would have resulted in excluding two animals from the BYP group and one animal from the DOM group. This would result in 59 ± 20 and 64 ± 16 successful visits (mean ± SD) for BYP and DOM, respectively, while enteric CH_4 production values would be 373 and 399 ± 21.1 g/day (estimated marginal mean ± SEM) for BYP and DOM, respectively.

The results of this study, in which dairy cow diets were optimised based on greenhouse gas emissions from the production of feed ingredients, highlight the importance of diet formulation for the environmental sustainability of dairy production. It is especially relevant when feeding strategies and the inclusion of certain ingredients are adjusted in order to mitigate enteric CH_4 emissions, as specific choices can result in trade-offs. Feed primary $CO_{2\text{-eq}}$ emissions and feed primary $CO_{2\text{-eq}}$ per kg ECM were lower for the BYP and DOM diets compared with CON, while feed primary $CO_{2\text{-eq}}$ per kg milk was lower only for the BYP diet compared with CON. We did not observe any differences in CH_4 production and CH_4 yield or intensity, and can thus conclude that the BYP and DOM diets outperformed CON in terms of carbon footprint when $CO_{2\text{-eq}}$ from feed production and enteric CH_4 are considered. Further research can incorporate the greenhouse gas contribution of ingredient transportation and manure management, providing a more nuanced comparison of the treatments. These results suggest that high-yielding milk production systems can be maintained even with high dependence on by-products and domestic feeds without compromising milk production or increasing greenhouse gas emissions from feed and enteric CH_4.

Limitations of this study

It is important to note that this study focused on the environmental sustainability of dairy production, focusing only on greenhouse gas emissions from feed production and direct emissions from animals. The calculations exclude emissions that occur during feed transport, processing, manure storage and handling. The significance of these emissions may vary based on factors such as transport methods, the use of renewable energy, technologies and geographical location (Henriksson et al., 2014). Specifically, the environmental impact of feed transport is influenced by the transportation methods and the length of the supply chain (Mogensen et al., 2014). For instance, emissions from short transportation distances (e.g. 100 km), such as those anticipated for the DOM diet, contribute less than 1% of the dairy ration carbon footprint. However, for long-distance transportation (e.g. 300 km), these emissions increase to approximately 3% of the dairy ration carbon footprint (Henriksson et al., 2014). Considering that the ingredients of BYP and DOM are sourced either domestically or from Northern Europe, the additional transportation emissions are expected to have a minor impact on the comparison among treatments. Emissions occurring during manure management and storage are mainly in the form of CH_4 and N_2O, and the magnitude of emissions is dependent on, e.g. storage system, temperature and cover (Kupper et al., 2020). A life cycle assessment may be used in a complementary study to make a comprehensive sustainability evaluation. The experimental diets are relevant for intensive dairy production in Scandinavia and northern Europe. However, diet composition varies across countries and regions due to factors such as ingredient quality and availability, climate conditions, soil type and infrastructure. The diets in this study were formulated for high milk yield, requiring high proportions of concentrate and using first-cut grass-legume mixture silage. The scenario may differ in practical dairy farming, e.g. late lactation animals may receive a mix of second- and third-cut silage.

The carbon footprint of feed ingredients, determined through economic allocation, is susceptible to price fluctuations and market conditions (Ardente and Cellura, 2012). Furthermore, changes in industrial processes that alter the feed value may have an impact on production and CH_4 emissions. Adoption of DOM or BYP diets on a large scale might result in challenges of resource availability and price fluctuations, which, in turn, affect the results of economic allocation. We assumed a marginal effect of our diets on the food system, but exploring these changes could be the focus of future modelling studies.

Supplementary material

Supplementary Material for this article (https://doi.org/10.1016/j.animal.2025.101544) can be found at the foot of the online page, in the Appendix section.

Ethics approval

The experiment complied with Swedish regulations and the guidelines set by EU Directive 2010/63/EU (European Union, 2010) on animal research. The procedures reported here were conducted with the approval of the Gothenburg Research Animal Ethics Committee (Dnr 5.8.18-14151/2022).

Data and model availability statement

None of the data were deposited in an official repository. The data and the model used are available upon request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors utilised OpenAI ChatGPT4 for grammar and spelling checks. The authors have reviewed and edited the content as needed and took full responsibility for the content of the publication.

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Declaration of interest

None.

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References

Aguerre, M.J., Wattiaux, M.A., Powell, J.M., Broderick, G.A., Arndt, C., 2011. Effect of forage-to-concentrate ratio in dairy cow diets on emission of methane, carbon dioxide, and ammonia, lactation performance, and manure excretion. Journal of Dairy Science 94, 3081–3093. https://doi.org/10.3168/jds.2010-4011.

Åkerlind, M., Weisbjerg, M., Eriksson, T., Udén, P., Ólafsson, B.L., Harstad, O., Volden, H., 2011. Feed analyses and digestion methods. In: Volden, H. (Ed.), NorFor – The Nordic Feed Evaluation System. Wageningen Academic Publishers, Wageningen, the Netherlands, pp. 41–54. https://doi.org/10.3920/978-90-8686-718-9.

Ardente, F., Cellura, M., 2012. Economic allocation in life cycle assessment: the state of the art and discussion of examples. Journal of Industrial Ecology 16, 387–398. https://doi.org/10.1111/j.1530-9290.2011.00434.x.

Arthur, P.F., Barchia, I.M., Weber, C., Bird-Gardiner, T., Donoghue, K.A., Herd, R.M., Hegarty, R.S., 2017. Optimizing test procedures for estimating daily methane and carbon dioxide emissions in cattle using short-term breath measures. Journal of Animal Science 95, 645–656. https://doi.org/10.2527/jas.2016.0700.

Beauchemin, K.A., Ungerfeld, E.M., Abdalla, A.L., Alvarez, C., Arndt, C., Becquet, P., Benchaar, C., Berndt, A., Mauricio, R.M., McAllister, T.A., Oyhantçabal, W., Salami, S.A., Shalloo, L., Sun, Y., Tricarico, J., Uwizeye, A., De Camillis, C., Bernoux, M., Robinson, T., Kebreab, E., 2022. Invited review: Current enteric methane mitigation options. Journal of Dairy Science 105, 9297–9326. https://doi.org/10.3168/jds.2022-22091.

Billen, G., Aguilera, E., Einarsson, R., Garnier, J., Gingrich, S., Grizzetti, B., Lassaletta, L., Le Noë, J., Sanz-Cobena, A., 2021. Reshaping the European agro-food system and closing its nitrogen cycle: the potential of combining dietary change, agroecology, and circularity. One Earth 4, 839–850. https://doi.org/10.1016/j.oneear.2021.05.008.

Chai, W., Udén, P., 1998. An alternative oven method combined with different detergent strengths in the analysis of neutral detergent fibre. Animal Feed Science and Technology 74, 281–288.

Cheng, L., Zhang, X., Reis, S., Ren, C., Xu, J., Gu, B., 2022. A 12% switch from monogastric to ruminant livestock production can reduce emissions and boost crop production for 525 million people. Nature Food 3, 1040–1051. https://doi.org/10.1038/s43016-022-00661-1.

Cherif, C., Hassanat, F., Claveau, S., Girard, J., Gervais, R., Benchaar, C., 2018. Faba bean (Vicia faba) inclusion in dairy cow diets: effect on nutrient digestion, rumen fermentation, nitrogen utilization, methane production, and milk performance. Journal of Dairy Science 101, 8916–8928. https://doi.org/10.3168/jds.2018-14890.

Donadia, A.B., Torres, R.N.S., Silva, H.M.D., Soares, S.R., Hoshide, A.K., Oliveira, A.S.D., 2023. Factors affecting enteric emission methane and predictive models for dairy cows. Animals 13, 1857. https://doi.org/10.3390/ani13111857.

Dressler, E.A., Bormann, J.M., Weaber, R.L., Rolf, M.M., 2023. Characterization of the number of spot samples required for quantification of gas fluxes and metabolic heat production from grazing beef cows using a GreenFeed. Journal of Animal Science 101, skad176. https://doi.org/10.1093/jas/skad176.

EC, 2005. European Commission Regulation (EC) No 183/2005 of the 12 January 2005 Laying Down requirements for feed hygiene. Official Journal of the European Union L/35. 8.2.2005. The European Commission, Brussels, Belgium.

EC, 2009. European Commission Regulation (EC) No 152/2009 of the 27 January 2009 Laying Down the Methods of Sampling and Analysis for the Official Control of Feed. H. Determination of Crude Oils and Fats, Procedure B in Official Journal of the European Union L/54. 26.2.2009. The European Commission, Brussels, Belgium.

Enahoro, D., Tran, N., Chan, C.Y., Komarek, A., Rich, K.M., 2021. The future of animal-source food demand and supply in Africa. Retrieved on 16 January 2023 from https://doi.org/10.31235/osf.io/fswmj.

Ertl, P., Zebeli, Q., Zollitsch, W., Knaus, W., 2016. Feeding of wheat bran and sugar beet pulp as sole supplements in high-forage diets emphasizes the potential of dairy cattle for human food supply. Journal of Dairy Science 99, 1228–1236. https://doi.org/10.3168/jds.2015-10285.

European Union. 2010. Directive 2010/63/EU of the European Parliament and of the Council of 22 September 2010 on the protection of animals used for scientific purposes. Official Journal of the European Union L276, 33–79.

FAO. 2018. The future of food and agriculture – Alternative pathways to 2050. FAO, Rome, Italy.

FAO, 2023. Pathways towards lower emissions – A global assessment of the greenhouse gas emissions and mitigation options from livestock agrifood systems. FAO, Rome, Italy. https://doi.org/10.4060/cc9029en.

Fox, J., Weisberg, S., 2019. An R companion to applied regression, 3rd edition. Sage Publications, Thousand Oaks, CA, USA. https://socialsciences.mcmaster.ca/jfox/Books/Companion/.

Frehner, A., Cardinaals, R.P.M., de Boer, I.J.M., Muller, A., Schader, C., van Selm, B., van Hal, O., Pestoni, G., Rohrmann, S., Herrero, M., van Zanten, H.H.E., 2022. The compatibility of circularity and national dietary recommendations for animal products in five European countries: a modelling analysis on nutritional feasibility, climate impact, and land use. The Lancet Planetary Health 6, e475–e483. https://doi.org/10.1016/S2542-5196(22)00119-X.

Garcia-Launay, F., Van Der Werf, H.M.G., Nguyen, T.T.H., Le Tutour, L., Dourmad, J.Y., 2014. Evaluation of the environmental implications of the incorporation of feed-use amino acids in pig production using life cycle assessment. Livestock Science 161, 158–175. https://doi.org/10.1016/j.livsci.2013.11.027.

Gerber, P., Vellinga, T., Opio, C., Steinfeld, H., 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. Livestock Science 139, 100–108. https://doi.org/10.1016/j.livsci.2011.03.012.

Global Feed LCA Institute, 2019. GFLI Feed Dataset. Retrieved on 19 November 2021 from https://globalfeedlca.org.

Guinguina, A., Krizsan, S.J., Huhtanen, P., 2021. Postpartum responses of dairy cows supplemented with cereal grain or fibrous by-product concentrate. Livestock Science 248, 104506. https://doi.org/10.1016/j.livsci.2021.104506.

Halmemies-Beauchet-Filleau, A., Rinne, M., Lamminen, M., Mapato, C., Ampapon, T., Wanapat, M., Vanhatalo, A., 2018. Review: Alternative and novel feeds for ruminants: nutritive value, product quality and environmental aspects. Animal 12, s295–s309. https://doi.org/10.1017/S1751731118002252.

Henriksson, M., Cederberg, C., Swensson, C., 2014. Carbon footprint and land requirement for dairy herd rations: impacts of feed production practices and regional climate variations. Animal 8, 1329–1338. https://doi.org/10.1017/S1751731114000627.

Hof, G., Vervoorn, M.D., Lenaers, P.J., Tamminga, S., 1997. Milk urea nitrogen as a tool to monitor the protein nutrition of dairy cows. Journal of Dairy Science 80, 3333–3340. https://doi.org/10.3168/jds.S0022-0302(97)76309-4.

IPCC, 2019. Summary for policymakers. In Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (ed. Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J.). Cambridge University Press, Cambridge, UK, pp. 1–28. https://doi.org/10.1017/9781009157988.001.

Jennische, P., Larsson, K., 1990. Traditionella svenska analysmetoder för foder och växtmaterial [Traditional Swedish analytical methods for feed and plant material]. Rapport 60. Statens Lantbrukskemiska Laboratorium, Uppsala, Sweden. [In Swedish].

Johnston, D.J., Theodoridou, K., Gordon, A.W., Yan, T., McRoberts, W.C., Ferris, C.P., 2019. Field bean inclusion in the diet of early-lactation dairy cows: effects on performance and nutrient utilization. Journal of Dairy Science 102, 10887–10902. https://doi.org/10.3168/jds.2019-16513.

Karlsson, J.O., Carlsson, G., Lindberg, M., Sjunnestrand, T., Röös, E., 2018b. Designing a future food vision for the Nordics through a participatory modeling approach. Agronomy for Sustainable Development 38, 59. https://doi.org/10.1007/s13593-018-0528-0.

Karlsson, J., Spörndly, R., Lindberg, M., Holtenius, K., 2018a. Replacing human-edible feed ingredients with by-products increases net food production efficiency in dairy cows. Journal of Dairy Science 101, 7146–7155. https://doi.org/10.3168/jds.2017-14209.

Karlsson, J., Ramin, M., Kass, M., Lindberg, M., Holtenius, K., 2019. Effects of replacing wheat starch with glycerol on methane emissions, milk production, and feed efficiency in dairy cows fed grass silage-based diets. Journal of Dairy Science 102, 7927–7935. https://doi.org/10.3168/jds.2018-15629.

Kupper, T., Häni, C., Neftel, A., Kincaid, C., Bühler, M., Amon, B., VanderZaag, A., 2020. Ammonia and greenhouse gas emissions from slurry storage – A review. Agriculture, Ecosystems & Environment 300, 106963. https://doi.org/10.1016/j.agee.2020.106963.

Larsson, K., Bengtsson, S., 1983. Determination of non-structural carbohydrates in plant material. Method description No. 22. National Laboratory for Agricultural Chemistry, Uppsala, Sweden. [In Swedish].

Lenth, R., 2023. Emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.8.4-1. Retrieved on 10 February 2025 from: https://CRAN.R-project.org/package=emmeans.

Lin, F., Li, X., Jia, N., Feng, F., Huang, H., Huang, J., Fan, S., Ciais, P., Song, X.-P., 2023. The impact of Russia-Ukraine conflict on global food security. Global Food Security 36, 100661. https://doi.org/10.1016/j.gfs.2022.100661.

Lindberg, M., Henriksson, M., Bååth Jacobsson, S., Berglund Lundberg, M., 2021. Byproduct-based concentrates in Swedish dairy cow diets – evaluation of environmental impact and feed costs. Acta Agriculturae Scandinavica, Section A — Animal Science 70, 132–144. https://doi.org/10.1080/09064702.2021.1976265.

Madsen, J., Bjerg, B.S., Hvelplund, T., Weisbjerg, M.R., Lund, P., 2010. Methane and carbon dioxide ratio in excreted air for quantification of the methane production from ruminants. Livestock Science 129, 223–227. https://doi.org/10.1016/j.livsci.2010.01.001.

Manafiazar, G., Zimmerman, S., Basarab, J., 2016. Repeatability and variability of short-term spot measurement of methane and carbon dioxide emissions from beef cattle using GreenFeed emissions monitoring system. Canadian Journal of Animal Science 96, 302–309. https://doi.org/10.1139/cjas-2015-0190.

Mehtiö, T., Rinne, M., Nyholm, L., Mäntysaari, P., Sairanen, A., Mäntysaari, E.A., Pitkänen, T., Lidauer, M.H., 2016. Cow-specific diet digestibility predictions based on near-infrared reflectance spectroscopy scans of faecal samples. Journal of Animal Breeding and Genetics 133, 115–125. https://doi.org/10.1111/jbg.12183.

Meijaard, E., Brooks, T.M., Carlson, K.M., Slade, E.M., Garcia-Ulloa, J., Gaveau, D.L.A., Lee, J.S.H., Santika, T., Juffe-Bignoli, D., Struebig, M.J., Wich, S.A., Ancrenaz, M., Koh, L.P., Zamira, N., Abrams, J.F., Prins, H.H.T., Sendashonga, C.N., Murdiyarso, D., Furumo, P.R., Macfarlane, N., Hoffmann, R., Persio, M., Descals, A., Szantoi, Z., Sheil, D., 2020. The environmental impacts of palm oil in context. Nature Plants 6, 1418–1426. https://doi.org/10.1038/s41477-020-00813-w.

Mills, J.A.N., Kebreab, E., Yates, C.M., Crompton, L.A., Cammell, S.B., Dhanoa, M.S., Agnew, R.E., France, J., 2003. Alternative approaches to predicting methane emissions from dairy cows. Journal of Animal Science 81, 3141–3150. https://doi.org/10.2527/2003.81123141x.

Mogensen, L., Kristensen, T., Nguyen, T.L.T., Knudsen, M.T., Hermansen, J.E., 2014. Method for calculating carbon footprint of cattle feeds – including contribution from soil carbon changes and use of cattle manure. Journal of Cleaner Production 73, 40–51. https://doi.org/10.1016/j.jclepro.2014.02.023.

Muscat, A., de Olde, E.M., Ripoll-Bosch, R., van Zanten, H.H.E., Metze, T.A.P., Termeer, C.J.A.M., van Ittersum, M.K., de Boer, I.J.M., 2021. Principles, drivers and opportunities of a circular bioeconomy. Nature Food 2, 561–566. https://doi.org/10.1038/s43016-021-00340-7.

Nielsen, P.P., Pettersson, G., Svennersten-Sjaunja, K.M., Norell, L., 2010. Technical note: variation in daily milk yield calculations for dairy cows milked in an automatic milking system. Journal of Dairy Science 93, 1069–1073. https://doi.org/10.3168/jds.2009-2419.

Nielsen, N.I., Volden, H., Åkerlind, M., Brask, M., Hellwing, A.L.F., Storlien, T., Bertilsson, J., 2013. A prediction equation for enteric methane emission from dairy cows for use in NorFor. Acta Agriculturae Scandinavica, Section A — Animal Science 63, 126–130. https://doi.org/10.1080/09064702.2013.851275.

Niu, P., Schwarm, A., Bonesmo, H., Kidane, A., Aspeholen Åby, B., Storlien, T.M., Kreuzer, M., Alvarez, C., Sommerseth, J.K., Prestløkken, E., 2021. A basic model to predict enteric methane emission from dairy cows and its application to update operational models for the national inventory in Norway. Animals 11, 1891. https://doi.org/10.3390/ani11071891.

Nocek, J.E., Russell, J.B., 1988. Protein and energy as an integrated system: relationship of ruminal protein and carbohydrate availability to microbial synthesis and milk production. Journal of Dairy Science 71, 2070–2107. https://doi.org/10.3168/jds.S0022-0302(88)79782-9.

Nordic Committee on Food Analysis, 1976. Nitrogen. Determination in food and feed according to Kjeldahl. 3rd ed. Nordic Committee on Food Analysis, Stockholm, Sweden.

NorFor, 2011. NorFor – The Nordic feed evaluation system. Wageningen Academic Publishers, Wageningen, the Netherlands. https://doi.org/10.3920/978-90-8686-718-9.

Nousiainen, J., Shingfield, K.J., Huhtanen, P., 2004. Evaluation of milk urea nitrogen as a diagnostic of protein feeding. Journal of Dairy Science 87, 386–398. https://doi.org/10.3168/jds.S0022-0302(04)73178-1.
Pang, D., Yan, T., Trevisi, E., Krizsan, S.J., 2018. Effect of grain- or by-product-based concentrate fed with early- or late-harvested first-cut grass silage on dairy cow performance. Journal of Dairy Science 101, 7133–7145. https://doi.org/10.3168/jds.2018-14449.
Patel, M., Sonesson, U., Hessle, A., 2017. Upgrading plant amino acids through cattle to improve the nutritional value for humans: effects of different production systems. Animal 11, 519–528. https://doi.org/10.1017/S1751731116001610.
Patra, A.K., 2013. The effect of dietary fats on methane emissions, and its other effects on digestibility, rumen fermentation and lactation performance in cattle: a meta-analysis. Livestock Science 155, 244–254. https://doi.org/10.1016/j.livsci.2013.05.023.
Pinheiro, J., Bates, D., R Core Team, 2022. nlme: Linear and nonlinear mixed effects models. R package version 3.1-160. Retrieved on 10 February 2025 from https://CRAN.R-project.org/package=nlme.
Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360, 987–992. https://doi.org/10.1126/science.aaq0216.
Posit team, 2022. RStudio: Integrated Development Environment for R. Posit Software, PBC, Boston, MA, USA. Retrieved on 10 February 2025 from: https://www.posit.co/.
Puhakka, L., Jaakkola, S., Simpura, I., Kokkonen, T., Vanhatalo, A., 2016. Effects of replacing rapeseed meal with fava bean at two concentrate crude protein levels on feed intake, nutrient digestion, and milk production in cows fed grass silage–based diets. Journal of Dairy Science 99, 7993–8006. https://doi.org/10.3168/jds.2016-10925.
R Core Team, 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved on 10 February 2025 from: https://www.R-project.org/.
Räisänen, S.E., Kuoppala, K., Rissanen, P., Halmemies-Beauchet-Filleau, A., Kokkonen, T., Vanhatalo, A., 2023. Effects of forage- and grain-legume-based silages supplemented with faba bean meal or rapeseed expeller on lactational performance, nitrogen utilization, and plasma amino acids in dairy cows. Journal of Dairy Science 106, 6903–6920. https://doi.org/10.3168/jds.2022-22997.
Ramin, M., Huhtanen, P., 2013. Development of equations for predicting methane emissions from ruminants. Journal of Dairy Science 96, 2476–2493. https://doi.org/10.3168/jds.2012-6095.
RKFS, 2021. Rules for calculation and communication of climate impact for feed in Sweden [Regler för beräkning och kommunikation av klimatpåverkan för foder i Sverige]. The Feed and Grain Association, Stockholm, Sweden. Retrieved on 21 October 2024 from https://www.foderochspannmal.se/_files/ugd/90417e_677c5cbcf4ab465abab7e15e219917ba.pdf.
Röös, E., Patel, M., Spångberg, J., Carlsson, G., Rydhmer, L., 2016. Limiting livestock production to pasture and by-products in a search for sustainable diets. Food Policy 58, 1–13. https://doi.org/10.1016/j.foodpol.2015.10.008.
Sawa, A., Bogucki, M., Krężel-Czopek, S., 2011. Effect of some factors on relationships between milk urea levels and cow fertility. Archives Animal Breeding 54, 468–476. https://doi.org/10.5194/aab-54-468-2011.
Sjaunja, L.O., Baevre, L., Junkkarinem, L., Pedersen, J., Setälä, J., 1990. A Nordic proposal for an energy corrected milk (ECM) formula. EAAP Publication No. 50. Center for Agricultural Publishing and Documentation (Pudoc), Wageningen, the Netherlands.
SJVFS, 2018. 2018:33, Saknr M39 Code of Statutes, Regulations and common advice concerning feed. The Swedish Board of Agriculture, Jönköping, Sweden. [In Swedish].
Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347, 1259855. https://doi.org/10.1126/science.1259855.
Takiya, C.S., Ylioja, C.M., Bennett, A., Davidson, M.J., Sudbeck, M., Wickersham, T.A., VandeHaar, M.J., Bradford, B.J., 2019. Feeding dairy cows with "leftovers" and the variation in recovery of human-edible nutrients in milk. Frontiers in Sustainable Food Systems 3, 114. https://doi.org/10.3389/fsufs.2019.00114.
Theurl, M.C., Lauk, C., Kalt, G., Mayer, A., Kaltenegger, K., Morais, T.G., Teixeira, R.F. M., Domingos, T., Winiwarter, W., Erb, K.-H., Haberl, H., 2020. Food systems in a zero-deforestation world: Dietary change is more important than intensification for climate targets in 2050. Science of the Total Environment 735, 139353. https://doi.org/10.1016/j.scitotenv.2020.139353.
van Dijk, M., Morley, T., Rau, M.L., Saghai, Y., 2021. A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. Nature Food 2, 494–501. https://doi.org/10.1038/s43016-021-00322-9.
van Hal, O., de Boer, I.J.M., Muller, A., de Vries, S., Erb, K.-H., Schader, C., Gerrits, W.J. J., van Zanten, H.H.E., 2019. Upcycling food leftovers and grass resources through livestock: impact of livestock system and productivity. Journal of Cleaner Production 219, 485–496. https://doi.org/10.1016/j.jclepro.2019.01.329.
van Knegsel, A.T.M., Van Den Brand, H., Dijkstra, J., Kemp, B., 2007. Effects of dietary energy source on energy balance, metabolites and reproduction variables in dairy cows in early lactation. Theriogenology 68, S274–S280. https://doi.org/10.1016/j.theriogenology.2007.04.043.
van Selm, B., Frehner, A., de Boer, I.J.M., van Hal, O., Hijbeek, R., van Ittersum, M.K., Talsma, E.F., Lesschen, J.P., Hendriks, C.M.J., Herrero, M., van Zanten, H.H.E., 2022. Circularity in animal production requires a change in the EAT-Lancet diet in Europe. Nature Food 3, 66–73. https://doi.org/10.1038/s43016-021-00425-3.
van Zanten, H.H.E., Mollenhorst, H., Klootwijk, C.W., van Middelaar, C.E., de Boer, I.J. M., 2016. Global food supply: land use efficiency of livestock systems. The International Journal of Life Cycle Assessment 21, 747–758. https://doi.org/10.1007/s11367-015-0944-1.
van Zanten, H.H.E., Herrero, M., van Hal, O., Röös, E., Muller, A., Garnett, T., Gerber, P. J., Schader, C., de Boer, I.J.M., 2018. Defining a land boundary for sustainable livestock consumption. Global Change Biology 24, 4185–4194. https://doi.org/10.1111/gcb.14321.
Växa, 2008. IndividRAM: För ökad lönsamhet. Program version 6.34 (6.3.4.8). Database version 6.65. [Computer software]. Växa Sweden. Retrieved on 11 November 2021 from: https://www.vxa.se.
Volden, H., Nielsen, N.I., 2011. Energy and metabolizable protein supply. In: Volden, H. (Ed.), NorFor – The Nordic Feed Evaluation System. Wageningen Academic Publishers, Wageningen, the Netherlands, pp. 81–83. https://doi.org/10.3920/978-90-8686-718-9.
Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., Takahashi, K., Vaughan, D., Wilke, C., Woo, K., Yutani, H., 2019. Welcome to the Tidyverse. Journal of Open Source Software 4, 1686. https://doi.org/10.21105/joss.01686.
Wickham, H., 2016. ggplot2: Elegant graphics for data analysis. Springer-Verlag, New York, NY, USA. https://ggplot2.tidyverse.org.
Wilkinson, J.M., 2011. Re-defining efficiency of feed use by livestock. Animal 5, 1014–1022. https://doi.org/10.1017/S175173111100005X.
Workie, E., Mackolil, J., Nyika, J., Ramadas, S., 2020. Deciphering the impact of COVID-19 pandemic on food security, agriculture, and livelihoods: a review of the evidence from developing countries. Current Research in Environmental Sustainability 2, 100014. https://doi.org/10.1016/j.crsust.2020.100014.
Yan, T., Mayne, C.S., Porter, M.G., 2006. Effects of dietary and animal factors on methane production in dairy cows offered grass silage-based diets. International Congress Series 1293, 123–126. https://doi.org/10.1016/j.ics.2006.02.024.
Zimmerman, P., Zimmerman, S., Utsumi, S., Beede, D., 2011. Development of a user-friendly online system to quantitatively measure metabolic gas fluxes from ruminants. Journal of Dairy Science 94, 760.

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

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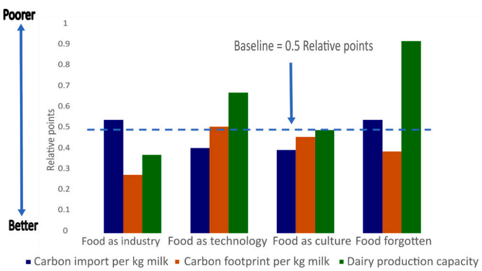
HIGHLIGHTS

- 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:

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

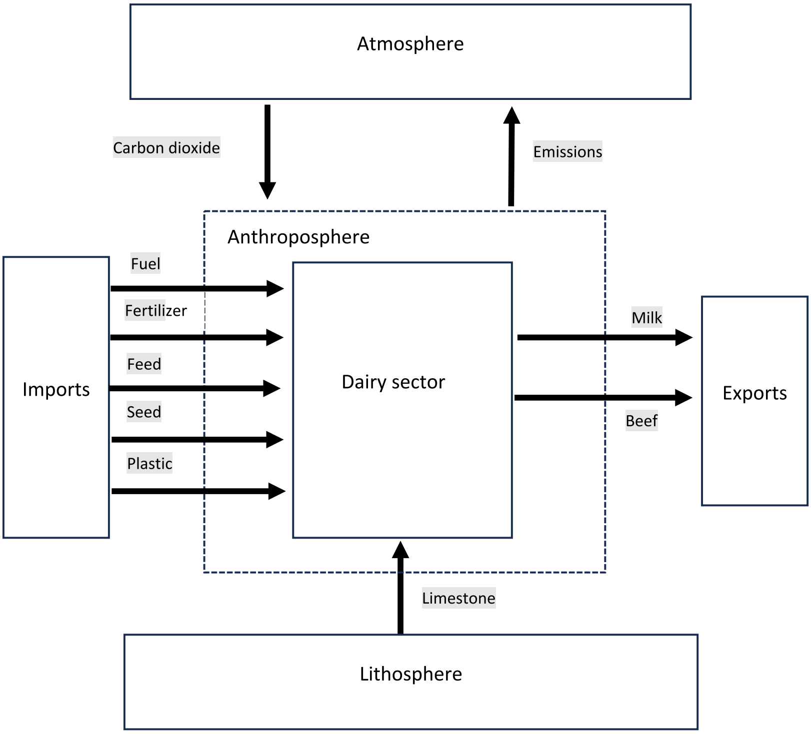

Fig. 1. The conceptual flow of carbon in the Norrmejerier's catchment area.

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

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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.

References

Aan den Toorn, S.I., Worrell, E., Van Den Broek, M.A., 2021. How much can combinations of measures reduce methane and nitrous oxide emissions from European livestock husbandry and feed cultivation? J. Clean. Prod. 304, 127138. https://doi.org/10.1016/j.jclepro.2021.127138.

Azzi, E.S., Li, H., Cederlund, H., Karltun, E., Sundberg, C., 2024. Modelling biochar long-term carbon storage in soil with harmonized analysis of decomposition data. Geoderma 441, 116761. https://doi.org/10.1016/j.geoderma.2023.116761.

Bengtsson, C., Thomasen, J.R., Kargo, M., Bouquet, A., Slagboom, M., 2022. Emphasis on resilience in dairy cattle breeding: possibilities and consequences. J. Dairy Sci. 105 (9), 7588–7599. https://doi.org/10.3168/jds.2021-21049.

Blomhoff, R., Andersen, R., Arnesen, E.K., Christensen, J.J., Eneroth, H., Erkkola, M., Gudanaviciene, I., Halldórsson, P.I., Höyer-Lund, A., Lemming, E.W., Meltzer, H.M., 2023. Nordic Nutrition Recommendations 2023: Integrating Environmental Aspects. Nordic Council of Ministers, Copenhagen, Denmark.

Brunner, P.H., Rechberger, H., 2017. Handbook of Material Flow Analysis for Environmental, Resource, and Waste Engineers, 2nd ed. CRC Press, Boca Raton.

Ecoinvent, 2023. Ecoinvent 3.9 database. Ecoinvent. Zurich, Switzerland.

Edström, M., Pettersson, O., Nilsson, L., Hörndahl, T., 2005. Jordbrukssektorns energianvändning. JTI, Uppsala (In Swedish).

FAO, GDP, 2019. Climate Change and the Global Dairy Cattle Sector – The Role of the Dairy Sector in a Low-Carbon Future. FAO, Rome, Italy.

Gerber, P., Vellinga, T., Opio, C., Steinfeld, H., 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. Livest. Sci. 139, 100–108. https://doi.org/10.1016/j.livsci.2011.03.012.

Gode, J., Martinsson, F., Hagberg, L., Öman, A., Höglund, J., Palm, D., 2011. Miljoefaktaboken 2011. Uppskattade emissionsfaktorer foer braenslen, el, vaerme och transporter. Värmeforsk, Stockholm, Sverige (In Swedish).

Google, 2023. Maps. https://www.google.se/maps/@62.9306328,19.1298491,6z?entry=ttu (accessed 14 December 2023).

Gordon, L., Holmgren, K.E., Bengtsson, J., Persson, M., Peterson, G., Röös, E., Wood, A., Alvstad, R., Basnet, S., Bunge, A.C., Jonell, M., Fetzer, I., 2022. Mistra Food Futures Report #1. Food as Industry, Food Tech or Culture, or Even Food Forgotten?: A Report on Scenario Skeletons of Swedish Food Futures. Swedish University of Agricultural Sciences, Uppsala, Sweden.

Grandl, F., Furger, M., Kreuzer, M., Zehetmeier, M., 2019. Impact of longevity on greenhouse gas emissions and profitability of individual dairy cows analysed with different system boundaries. Animal 13 (1), 198–208. https://doi.org/10.1017/S175173111800112X.

Gross, C.D., Bork, E.W., Carlyle, C.N., Chang, S.X., 2022. Biochar and its manure-based feedstock have divergent effects on soil organic carbon and greenhouse gas emissions in croplands. Sci. Total Environ. 806, 151337. https://doi.org/10.1016/j.scitotenv.2021.151337.

Guillaume, T., Makowski, D., Libohova, Z., Bragazza, L., Sallaku, F., Sinaj, S., 2022. Soil organic carbon saturation in cropland-grassland systems: storage potential and soil quality. Geoderma 406, 115529. https://doi.org/10.1016/j.geoderma.2021.115529.

Hammar, T., Hansson, P.-A., Röös, E., 2022. Time-dependent climate impact of beef production – can carbon sequestration in soil offset enteric methane emissions? J. Clean. Prod. 331, 129948. https://doi.org/10.1016/j.jclepro.2021.129948.

Henryson, K., Meurer, K.H., Bolinder, M.A., Kätterer, T., Tidåker, P., 2022. Higher carbon sequestration on Swedish dairy farms compared with other farm types as revealed by national soil inventories. Carbon Managem. 13 (1), 266–278. https://doi.org/10.1080/17583004.2022.2074315.

Hoang, D.L., Wiersema, B., Moll, H.C., Nonhebel, S., 2021. The impact of biogas production on the organic carbon input to the soil of Dutch dairy farms: a substance flow analysis. J. Ind. Ecol. 26 (2), 491–508. https://doi.org/10.1111/jiec.13197.

Hristov, A.N., 2023. Perspective: could dairy cow nutrition meaningfully reduce the carbon footprint of milk production? J. Dairy Sci. 106 (11), 7336–7340. https://doi.org/10.3168/jds.2023-23461.

IDF, 2022. A Common Carbon Footprint Approach for the Dairy Sector: The IDF Guide to Standard Life Cycle Assessment Methodology. International Dairy Federation, Brussels, Belgium.

IPCC, 2006. IPCC Guidelines for National Greenhouse gas Inventories, vol. 4. IPCC, Geneva, Switzerland.

IPCC, 2014. Climate change 2014: Synthesis report. Contribution of working groups I. In: II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, p. 151.

IPCC, 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse gas Inventories, vol. 4. IPCC, Geneva, Switzerland.

IPCC, 2021. The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Karltun, E., Jacobson, A., Lennartsson, T., 2010. Inlagring av kol I betesmark. Jönköping, Swedish Board of Agriculture (In Swedish).

Krizsan, S.J., Chagas, J.C., Pang, D., Cabezas-Garcia, E.H., 2021. Sustainability aspects of milk production in Sweden. Grass Forage Sci. 76 (2), 205–214. https://doi.org/10.1111/gfs.12539.

Kyttä, V., Hyvönen, T., Saarinen, M., 2023. Land-use-driven biodiversity impacts of diets—a comparison of two assessment methods in a Finnish case study. Int. J. Life Cycle Assess. 28 (9), 1104–1116. https://doi.org/10.1007/s11367-023-02201-w.

Landquist, B., Behaderovic, D., 2021. Betydelsen av mjölkproduktion I Norrland sett ur miljö och systemperspektiv. RISE (In Swedish).

Lantmännen, 2019. Framtidens Jordbruk–- Vägen mot ett Klimatneutralt Jordbruk 2050. Available at: https://www.lantmannen.se/contentassets/8167a6266e48 4420ac6721499f690201/lantmannen_framtidens_jordbruk_final-version.pdf.

Li, S., Tasnady, D., 2023. Biochar for soil carbon sequestration: current knowledge, mechanisms, and future perspectives. C 9 (3), 67. https://doi.org/10.3390/c9030067.

Greenhouse gas emissions from dairy cows fed best practice diets. In: Managos, M., Lindahl, C., Agenäs, S., Sonesson, U., Lindberg, M., Scientific Committee (Eds.), 2023. Proceedings of 74th Annual Meeting of the European Federation of Animal Science (pg 935), Lyon, France, September 1 2023. Wageningen Academic Publishers. https://doi.org/10.3920/978-90-8686-936-7.

Nielsen, N.I., Volden, H., Åkerlind, M., Brask, M., Hellwing, A.L.F., Storlien, T., Bertilsson, J., 2013. A prediction equation for enteric methane emission from dairy cows for use in NorFor. Acta Agric. Scand. Sect. - Anim. Sci. 63, 126–130. https://doi.org/10.1080/09064702.2013.851275.

NorFor, 2011. The Nordic Feed Evaluation System. Brill | Wageningen Academic. The Netherlands.

Öhlund, E., Malmaeus, M., Fauré, E., 2020. The significance of different realms of value for agricultural land in Sweden. Land Use Policy 96, 104714. https://doi.org/10.1016/j.landusepol.2020.104714.

Pan, B., Xia, L., Lam, S.K., Wang, E., Zhang, Y., Mosier, A., Chen, D., 2022. A global synthesis of soil denitrification: driving factors and mitigation strategies. Agric. Ecosyst. Environ. 327, 107850. https://doi.org/10.1016/j.agee.2021.107850.

Peixoto, L., Petersen, S.O., 2023. Efficacy of three nitrification inhibitors to reduce nitrous oxide emissions from pig slurry and mineral fertilizers applied to spring barley and winter wheat in Denmark. Geoderma Reg. 32, e00597. https://doi.org/10.1016/j.geodrs.2022.e00597.

Ports.com, 2023. Sea route and distance. http://ports.com/sea-route/ (accessed 14 December 2023).

Printz, S., 2023. Klimatarbete på gård. Norrmejerier, Luleå, Sverige (In Swedish).

Rafiqul, I., Weber, C., Lehmann, B., Voss, A., 2005. Energy efficiency improvements in ammonia production—perspectives and uncertainties. Energy 30 (13), 2487–2504. https://doi.org/10.1016/j.energy.2004.12.004.

Rahman, M.M., Khan, I., Field, D.L., Techato, K., Alameh, K., 2022. Powering agriculture: present status, future potential, and challenges of renewable energy applications. Renew. Energy 188, 731–749. https://doi.org/10.1016/j.renene.2022.02.065.

Samsonstuen, S., Møller, H., Aamaas, B., Knudsen, M.T., Mogensen, L., Olsen, H.F., 2024. Choice of metrics matters—future scenarios on milk and beef production in Norway using an LCA approach. Livest. Sci. 279, 105393. https://doi.org/10.1016/j.livsci.2023.105393.

Schader, C., Drapela, T., Markut, T., Meier, M.S., Lindenthal, T., Hörtenhuber, S., Pfiffner, L., 2014. Farm-and product-level biodiversity assessment of conventional and organic dairy production in Austria. Int. J. Biodivers. Sci. Ecosyst. Servic. Manag. 10 (1), 20–39. https://doi.org/10.1080/21513732.2013.878752.

Searchinger, T., James, O., Dumas, P., 2022. Europe's Land Future? Opportunities to Use Europes Land to Fight Climate Change and Improve Biodiversity; and why Proposed Policies Could Undermine both. Princetown University, New Jersey, USA.

Shabir, I., Dash, K.K., Dar, A.H., Pandey, V.K., Fayaz, U., Srivastava, S., Nisha, R., 2023. Carbon footprints evaluation for sustainable food processing system development: a

comprehensive review. Future Foods 7, 100215. https://doi.org/10.1016/j.fufo.2023.100215.
Sharma, P., Humphreys, J., Holden, N.M., 2018. The environmental impact of dairy production on poorly drained soils under future climate scenarios for Ireland. J. Environ. Manag. 223, 625–632. https://doi.org/10.1016/j.jenvman.2018.06.074.
Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A.B., De Courcelles, V.D.R., Singh, K., Wheeler, I., 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agric. Ecosyst. Environ. 164, 80–99. https://doi.org/10.1016/j.agee.2012.10.001.
Struhs, E., Mirkouei, A., You, Y., Mohajeri, A., 2020. Techno-economic and environmental assessments for nutrient-rich biochar production from cattle manure: a case study in Idaho, USA. Appl. Energy 279, 115782. https://doi.org/10.1016/j.apenergy.2020.115782.
Suryanto, B.H., Matuszek, K., Choi, J., Hodgetts, R.Y., Du, H.L., Bakker, J.M., Kang, C.S., Cherepanov, P.V., Simonov, A.N., MacFarlane, D.R., 2021. Nitrogen reduction to ammonia at high efficiency and rates based on a phosphonium proton shuttle. Science 372 (6547), 1187–1191. https://doi.org/10.1126/science.abg2371.
Swedish Board of Agriculture, 2022. Livsmedelskonsumtion och näringsinnehåll. Uppgifter till och med 2021 https://jordbruksverket.se/om-jordbruksverket/jordbruksverkets-officiella-statistik/jordbruksverkets-statistikrapporter/statistik/2022-12-09-livsmedelskonsumtion-och-naringsinnehall.–uppgifter-till-och-med-2021#h-Direktkonsumtionenavlivsmedel (accessed 12 February 2024) (In Swedish).
Thivierge, M.N., Jégo, G., Bélanger, G., Chantigny, M.H., Rotz, C.A., Charbonneau, É., Baron, V.S., Qian, B., 2017. Projected impact of future climate conditions on the agronomic and environmental performance of Canadian dairy farms. Agric. Syst. 157, 241–257. https://doi.org/10.1016/j.agsy.2017.07.003.
Vuorisalo, T., Arjamaa, O., Vasemägi, A., Taavitsainen, J.P., Tourunen, A., Saloniemi, I., 2012. High lactose tolerance in north Europeans: a result of migration, not in situ milk consumption. Perspect. Biol. Med. 55 (2), 163–174. https://doi.org/10.1353/pbm.2012.0016.
Wall, A.M., Campbell, D.I., Mudge, P.L., Rutledge, S., Schipper, L.A., 2019. Carbon budget of an intensively grazed temperate grassland with large quantities of imported supplemental feed. Agric. Ecosyst. Environ. 281, 1–15. https://doi.org/10.1016/j.agee.2019.04.019.
Wilkinson, J.M., 2011. Re-defining efficiency of feed use by livestock. Animal 5 (7), 1014–1022. https://doi.org/10.1017/S175173111100005X.
Yu, X., Catanescu, C.O., Bird, R.E., Satagopan, S., Baum, Z.J., Lotti Diaz, L.M., Zhou, Q. A., 2023. Trends in research and development for CO2 capture and sequestration. ACS Omega 8 (13), 11643–11664. https://doi.org/10.1021/acsomega.2c05070.

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This thesis investigated how dairy ration formulation can reduce greenhouse gas emissions in Swedish high-producing dairy production without compromising productivity. Papers I and II were feeding trials testing low-carbon footprint concentrate mixes for dairy cows and the inclusion of whole-crop wheat silage in heifer diets. Paper III was a farm-level life cycle assessment assessing land use and greenhouse gas emissions of a modelled dairy farm. Paper IV was a regional scenario analysis exploring future pathways for dairy production in Northern Sweden.

Markos Managos received his PhD from the Department of Applied Animal Science and Welfare, Swedish University of Agricultural Sciences (SLU). He holds a MSc degree in Animal Science (SLU) and a veterinary degree from Aristotle University of Thessaloniki, Greece.

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