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Research Paper

When arable land is the limit: Paths for future livestock production – An example from Norway

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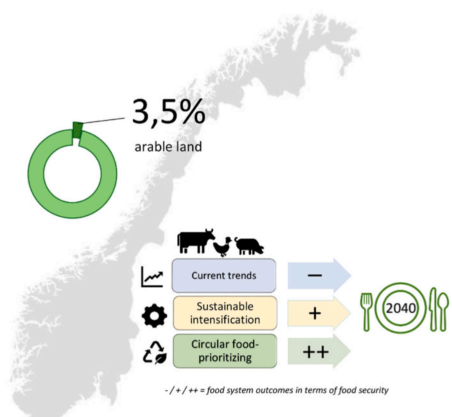
HIGHLIGHTS

- Three scenarios explore how livestock production in Norway could evolve by 2040 under different biomass use strategies.
- TrendProd reflects current trends, with high environmental impacts and animal protein supply far exceeding dietary recommendations.
- MoreProd increases productivity using domestic feed innovations, with moderate environmental impact and high land use.
- ChangeProd reduces environmental impacts and feed-food competition but requires dietary shifts and supportive policies.
- The study highlights the importance of combining efficiency, sufficiency, and strategic biomass use for sustainable food systems.

GRAPHICAL ABSTRACT



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ABSTRACT

Context: The global food system contributes significantly to environmental degradation, with livestock production driving greenhouse gas emissions and feed-food competition. Norway, with only 3.5 % arable land, faces challenges balancing food security with reducing environmental impacts.
Objective: This study examines future livestock production strategies in Norway to evaluate their environmental sustainability and resource efficiency. The focus is on three scenarios for 2040: *TrendProd* (baseline projection), *MoreProd* (increased productivity with circular bioeconomy initiatives), and *ChangeProd* (circular livestock production prioritizing food production over feed use).
Methods: Life cycle assessment was used to assess environmental impacts per kg of protein, complemented by resource efficiency evaluations through land use ratio (LUR) and nitrogen recycling index (NRI). Scenarios were

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analyzed at the national scale for their ability to supply animal-source foods (ASF) while reducing feed-food competition and enhancing biodiversity.
Results and conclusions: TrendProd reflected current trends, resulting in significant overproduction of animal protein relative to population needs based on dietary recommendations, along with high environmental impacts. *MoreProd* achieved slightly lower climate impact per kg protein, reduced biodiversity loss, and neutral land use efficiency but increased overall land use. *ChangeProd* prioritized low-opportunity-cost biomass, enhancing biodiversity and resource efficiency while reducing total production. This would necessitate dietary shifts to maintain domestic production sufficiency. A combination of efficiency and sufficiency strategies, supported by comprehensive policies, is essential for sustainable livestock production.
Significance: The findings highlight the potential for Norway to develop sustainable livestock systems that address environmental challenges while maintaining food security. The *ChangeProd* scenario provides a model for balancing food production with sustainability goals, offering insights for other countries facing similar challenges.

1. Introduction

Future food systems must provide food security for a growing global population while remaining within the Earth's environmental limits (FAO, 1996; Richardson et al., 2023). Food systems currently account for approximately one-third of anthropogenic greenhouse gas (GHG) emissions, with land use and land use change responsible for over 70 % of that share (Crippa et al., 2021). In Europe, food consumption contributes 30–40 % of an average citizen's climate footprint, with meat alone accounting for 30–60 % of that impact (Gonera et al., 2021; Sala et al., 2019). Livestock feed production occupies over 40 % of the global cropland (Mottet et al., 2017), limiting land available for growing food directly to humans (Muscat et al., 2020), despite strong public health recommendations to shift toward more plant-based diets (WHO, 2009). Also, animal-source foods (ASF) generally have a larger environmental impact than plant-based alternatives (Poore and Nemecek, 2018). Transforming these systems poses a major challenge, as they are deeply entangled with societal structures, health outcomes, and environmental trade-offs (FAO et al., 2023). Policy frameworks such as the European Union's Farm to Fork strategy aim to accelerate the shift toward just, healthy, and sustainable food systems (Bock et al., 2022), yet the transition pathways remain contested. While sustainable intensification emphasizes efficiency gains through technology, agroecological approaches advocate for ecological balance, nutrient recycling, and resilience (Godfray, 2015; Mockshell and Kamanda, 2018; Wezel et al., 2015). Given the diversity of regional contexts and resource bases, no single solution can be universally applied, and poorly tailored approaches risk undermining sustainability goals (Van Zanten et al., 2023; Ingram and Thornton, 2022).

Norway, a small non-EU country in Europe, faces distinct challenges in developing a sustainable food system. The country spans nearly 325.000 km^2 and is characterized by a long coastline, mountainous terrain, and northern latitude giving short growing seasons and a generally harsh and varied climate (Ketzler et al., 2021). Only 3.5 % of the land is arable often scattered across remote areas, posing practical constraints that affect production costs and efficiency (NIBIO, 2023). These conditions limit the potential for large-scale crop production, while vast grasslands and outfields make livestock production an important part of domestic food supply. Additionally, the long coastline supports large-scale aquaculture, particularly salmon farming, producing around 1.5 million tonnes annually (Finci et al., 2023). While Norway appears to have a high self-sufficiency rate (87 %) based on domestic production, this figure drops to 39 % in caloric terms when correcting for feed imports and subtracting exported fish (Aas et al., 2022; Finci et al., 2023; NIBIO, 2024a, 2024b).

To address food security and climate goals under these constraints, Norway has primarily pursued a strategy of sustainable intensification, seeking to increase food production through improved efficiency, high-value feed, genetic progress, and technological innovation (White Paper 11 (2016-2017); Bardalen et al., 2020). This path is further reinforced by strong public investment in innovation and by the national target to reduce GHG emissions from agriculture by 5 million tonnes by 2030 (Norwegian Farmers' Union, 2021). In contrast, the EU promotes a more agroecological trajectory through its Farm to Fork strategy, which emphasizes resilience, nutrient recycling, and reduced dependence on external inputs (e.g., FAO et al., 2023; van Zanten et al., 2023). These diverging strategies partly reflects different interpretations of sustainability, but also differences in biomass availability. While many EU countries have more arable land and access to crop residues, Norway's livestock production depends heavily on roughage, outfields, and imported feed. Adding complexity, nutritional guidelines recommending less red meat and more poultry may unintentionally compromise food system sustainability. Replacing ruminants with poultry could reduce the ability to utilize grasslands and agricultural by-products, increase reliance on concentrates and imported feed ingredients, and thereby intensify feed-food competition (van Selm et al., 2022).

Even though Norway is a wealthy country, its high reliance on imported food and feed makes it vulnerable to external disruptions, including trade instability, supply chain shocks, and climate-related events. Limited arable land further restricts its adaptive capacity, highlighting the need for more sustainable and efficient livestock strategies. A more resilient food system relies on diverse, locally adapted biomass sources and production systems that can buffer external disturbances while maintaining nutritional supply. A key aspect of this challenge is reducing feed-food competition. Crop production generates large volumes of biomass that are either inedible by humans (e.g., straw and grass from leys) or in direct demand (e.g., wheat bran). Such biomass can be redirected to livestock feed, fertilizers, or bio-based materials, enabling more arable land to be dedicated to food crops and improving overall system efficiency (van Zanten et al., 2016; Mottet et al., 2017).

Several recent studies have explored how livestock systems can become more sustainable through strategies such as circular resource flows and optimized biomass use (e.g., Karlsson et al., 2017; Röös et al., 2017; Karlsson et al., 2018; Van Selm et al., 2022; Heerschop et al., 2023; Van Selm et al., 2023; Simon et al., 2024). Against this backdrop, our study explores future livestock production strategies for Norway by 2040, comparing a sustainable intensification pathway with a circular, food-prioritizing system. The 2040 horizon reflects the longer timeframe needed for structural changes in livestock systems, including shifts in feed availability, infrastructure, and production practices, which are unlikely to be achieved by 2030, the target year for agricultural climate goals. We assess the impacts of these scenarios, alongside a reference based on current trends, on environmental sustainability, resource use efficiency, and the system's capacity to supply animal-source protein to the Norwegian population. The scenarios, except the *TrendProd* scenario, are grounded in the same domestic biomass currently used for livestock feed, supplemented with novel feed resources where applicable. To evaluate the environmental performance of the scenarios, we apply life cycle assessment (LCA). LCA offers a comprehensive, systems-based approach for quantifying environmental impacts across the value chain, making it particularly suited to assessing trade-offs between alternative food system strategies.

2. Material and methods

We developed a national-level model representing Norway's livestock sector in 2040, designed to simulate the use of domestic biomass under three production scenarios. The model integrates data on biomass availability, feed conversion, animal productivity, and dietary protein needs. It calculates resource flows and environmental impacts based on scenario-specific constraints, using a mix of statistical inputs, scenario assumptions, and optimization tools. The model is national in scope but incorporates regional variation in biomass yields. Norway was divided into administrative units for estimating biomass production and availability. However, feed allocation, livestock production, and environmental assessments were conducted at the national level. Thus, the spatial resolution of input data was higher than the resolution of outputs. A full overview of input data, parameters, and calculation steps is provided in Supplementary Tables S1–S17.

2.1. Scenario description

We used a reference scenario, *TrendProd*, based on projected trends for livestock production from 2017 to 2040. This scenario includes both domestic and imported feed ingredients and reflects a continuation of current practices. A second scenario, *MoreProd*, explores the use of only domestic feed resources while aiming to increase productivity per livestock unit. Production volumes of animal-source foods follow current trends, but imported protein sources (e.g., soybeans) are replaced by domestically produced alternatives, such as biorefined yeast and insects. A third scenario, *ChangeProd*, is dedicated to transforming livestock production systems by reducing feed-food competition through the strategic use of low-opportunity-cost biomass. In this scenario, *ChangeProd,* arable land is prioritized for food production, and livestock are used primarily to recycle by-products and biomass not suitable for direct human consumption. Hence production volumes of animal-source food are determined by the availability of such feed resources in this scenario. In all scenarios, crop production on arable land remains at current levels with 68 % of arable land allocated to ley cultivation for pasture and forage production, 24 % under cereal cultivation, 3 % used for oilseed and 3 % for legume. The remaining areas were used for potato, vegetable and fruit production. The crop production generated a certain amount of by-products, i.e., wheat bran, rape seed cake etc. These amounts are the same across the scenarios but the utilization of these as feed for the various livestock productions varies between the scenarios. See more detailed description of the use of biomass for feed in Chapter 2.1.2.

The baseline for the study consisted of real data from crop and livestock production in Norway in 2017, as this year formed the basis for the LCA models used (Møller et al., 2022; Samsonstuen et al., 2024). The *TrendProd* and *MoreProd* scenarios projected current food production trends, while the *ChangeProd* scenario was constrained by the availability and circular use of biomass. In *MoreProd*, human-edible biomass was permitted to increase livestock productivity per livestock unit, whereas in *ChangeProd,* it was only used for feed if surplus remained after meeting human consumption needs (e.g., barley). Due to the limited capacity for domestic protein crop cultivation in Norway, both alternative scenarios included novel protein sources (yeast, insects, grass protein). The resulting protein output for human consumption in each scenario was compared to the population's estimated dietary protein needs in year 2040. This assessment assumed a domestic population of 5.8 million inhabitants, with identical demographic projections across all scenarios, based on Statistics Norway (2023). Protein requirements were calculated by age group using Nordic Nutritional Recommendations (NNR., 2023), Svennerud and Steine (2011), and The Norwegian Food Composition Table (NFSA, 2023).

2.1.1. Livestock production

The modelling of livestock production differed across the three scenarios depending on how biomass was allocated (Table 1). In *TrendProd* and *MoreProd,* livestock populations and the total production of animal-source foods (milk, beef, poultry meat, pork, and eggs) were based on projected trends. In *ChangeProd*, production was constrained by the availability of domestic biomass, and livestock numbers were adjusted accordingly. Assumptions were made about genetic progress in productivity by 2040 (Table 1). For cattle, it was assumed that the average milk and meat yield per cow would match the best-performing quartile of Norwegian herds in 2017. For pigs, performance levels were based on the best quartile of Specific Pathogen Free (SPF) herds. For poultry, no distribution data were available, so average 2017 productivity was used.

Table 1
Number of livestock, production parameters, and total protein production from livestock assumed in the three 2040 scenarios: TrendProd (reference scenario following current trends), MoreProd (maximized livestock production on domestic feed), and ChangeProd (livestock production on domestic feed with avoided feed-food competition). The number of animals is calculated based on available biomass for feed and assumed yield for each scenario. The total feed intake per year is based on the number of animals, yield, and assumed feed requirements. Beef cattle and chicken were omitted from the ChangeProd scenario, due to feed allocation strategies, as explained in Chapter 2.1.3.

	TrendProd	*MoreProd*	*ChangeProd*
Dairy cattle			
Total dairy cows (LU[a])	188,730	188,730	300,953
Total heifers (LU)	165,941	196,080	312,674
Total bulls (LU)	113,130	143,238	264,420
Milk (kg FPCM cow^{-1} $year^{-1}$)	10,487	10,487	6576
Carcass production (kg cow^{-1} $year^{-1}$)[b]	298	301	274
Feed intake, dairy cow (MJ LU^{-1} $year^{-1}$)[c]	48,750	47,270	34,735
Feed intake, heifer (MJ LU^{-1} $year^{-1}$)[c]	14,089	13,920	13,741
Feed intake, young bulls (MJ LU^{-1} $year^{-1}$)[c]	14,283	13,804	12,535
Beef cattle			
Total beef cows (LU)	116,883	136,490	–
Total heifers (LU)	126,833	157,662	–
Total bulls (LU)	81,206	97,563	–
Carcass production (kg cow^{-1} $year^{-1}$)	345	291	–
Feed intake, beef cow (MJ LU^{-1} $year^{-1}$)	17,907[b]	16,127[c]	–
Feed intake, heifer (MJ LU^{-1} $year^{-1}$)	12,995[b]	11,784[c]	–
Feed intake, young bulls (MJ LU^{-1} $year^{-1}$)	17,247[b]	13,555[c]	–
Pigs[d]			
Total population finishers	1,887,160	1,569,901	962,452
Carcass weight (kg $animal^{-1}$)	81.5	81.5	81.5
Feed units/kg gain (kg)	2.49	2.49	2.49
Chicken			
Total population	81,345,876	69,826,339	–
Carcass weight (kg $animal^{-1}$)	1.38	1.38	–
Feed units/kg carcass (kg)	2.22	2.22	–
Laying hen[e]			
Total population	4,270,226	4,270,226	4,270,226
Egg weight (kg $animal^{-1}$)	20.4	20.4	20.4
Feed/kg egg (kg)	2.03	2.03	2.03
Total protein production from livestock	122,613,362	116,779,516	96,070,582

[a] LU = livestock units (sum of the number of days over individual animals in the category divided by 365 days).
[b] Total slaughter production per cow, including slaughtered bulls, surplus heifers and culled cows.
[c] Feed intake for dairy cows was obtained using the Nordic feed evaluation system (NorFor; Volden, 2011) through TINE Optifor, including 3 % wastage.
[d] Specific pathogen free (SPF) based on the best quartile of SPF herds in 2017.
[e] TrendProd and MoreProd: 100 % free-run; ChangeProd: cages with enriched housing, free-range.

Due to the lack of an LCA model for sheep, they were excluded from the modeled production outputs, but their feed demand was included, thereby reducing biomass available to other livestock categories.

Final outputs of milk, meat, and eggs were estimated using livestock population sizes and average productivity per animal, using performance data from 2017 (adjusted for expected genetic improvement by 2040) (Table 1). For monogastric animals, production was estimated using feed demand per product unit. For ruminants, feed rations were optimized using the NorFor system (Volden, 2011), which allowed us to simulate how the energy content of available biomass influenced milk yield per cow. This was especially relevant in the *ChangeProd* scenario, where the dairy cow feed ration contained nearly 30 % less energy than in the other scenarios. As a result, milk yield per cow dropped by almost 40 %, necessitating a 60 % increase in the number of dairy cows to maintain constant national milk production. This change led to higher beef output and enabled dairy cows to replace beef cattle in the system.

The basic principles for allocating feed resources varied between the scenarios (see Chapter 2.1.3), as did the resulting production parameters (Table 1). For pigs, chickens, and laying hens, carcass and egg weights, as well as feed intake per animal, were assumed to remain constant across scenarios. However, the number of animals varied significantly depending on the availability of suitable feed. In the *MoreProd* and *ChangeProd* scenarios, pig numbers declined by 17 % and nearly 50 %, respectively, compared to *TrendProd*. Chicken production decreased by 14 % in *MoreProd* and was eliminated entirely in *ChangeProd*, as chickens were not prioritized in the feed allocation hierarchy due to their lower suitability for by-product and waste-based diets. These adjustments led to a total protein output in *MoreProd* that was nearly 5 % lower than in *TrendProd*, while the *ChangeProd* scenario saw an additional 18 % reduction due to the focus on minimizing feed-food competition. See detailed description of assumptions made of livestock production in Supplementary Tables S11-S15.

2.1.2. Feed

Feed resources in the *TrendProd* scenario consisted of both imported feed and domestic feed resources. Imported feed ingredients were used only in the *TrendProd* scenario. These included soybean meal, rapeseed cake, beet pulp, molasses, limestone meal, maize, palm oil, and some vitamins and minerals. The total quantity and composition are provided in Supplementary Table S2. The LCA data for environmental impact of the imported feed was based on the Ecoinvent (Wernet et al., 2016) and the Agri-footprint databases (Blonk Consultants, 2017). For soybean meal, no emissions related to land use change were included as all soybeans imported to Norway are certified as deforestation-free and thus comply with the 20-year rule (BSI, 2011; ISO, 2018; IPCC, 2003). The domestic feed biomass consisted of grains, grass, outfield pasture, biorefined feed ingredients (yeast, insects, and green protein processed from grass), and by-products and residuals (wheat bran, brewer's spent grain and yeast, food waste from food industry, crop residues, vegetable residuals (beet tops, loss, and waste), potato residuals, fishmeal, and also rendered fat and meat and bone meal from pig and poultry, assuming this will be allowed within 2040) from the food system. For the crop production and grass production on outfields, weighted averages for domestic yields for different areas were calculated (Supplementary Tables S1-S6). In the *ChangeProd* scenario, a key aim was to maximize the use of underutilized roughage resources, including outfield pastures, to reduce feed-food competition and improve resource efficiency. While some grasslands are also used in *TrendProd* and *MoreProd*, the extent of grazing is more limited due to lower ruminant numbers or a greater emphasis on harvested forage. Thus, not all available pasture is grazed in these scenarios. The quantity of biorefined feed ingredients was determined based on the availability of raw materials, such as the amount of food waste available as substrates for insect production, see full description in Supplementary Tables S7-S10.

2.1.3. Feed allocation hierarchy

To support Norway's goal of maintaining nationwide food production and recognizing the central role of milk as both a key dietary component and a foundation of agricultural policy, per capita milk consumption was held constant across all scenarios. Consequently, dairy cows were prioritized in the feed allocation hierarchy. However, protein efficiency measured in terms of kg protein (*MoreProd*) or kg human digestible protein (*ChangeProd*) produced in the various animal systems was also evaluated according to the objectives of each scenario, as detailed in Supplementary Table S16. Feed ingredient suitability was carefully considered for each livestock system, ensuring balanced diets that meet protein requirements. The diet composition for dairy and beef cattle was optimized based on available feed resources using NorFor in each scenario. For monogastric animals, the diets were based on the crude protein content of the feed and in addition net energy for pigs and nitrogen-corrected apparent metabolizable energy for chickens and laying hens.

In the *MoreProd* scenario, which emphasizes productivity and efficiency, monogastric animals were prioritized in the feed allocation to maximize production yield (e.g., Bonesmo and Enger, 2021). Conversely, in the *ChangeProd* scenario—focused on converting non-edible or less demanded biomass into food—ruminants were prioritized in the feed allocation hierarchy (e.g., van Hal et al., 2019; Karlsson et al., 2020). Ruminants, with their ability to convert plant biomass into protein via microorganisms, can reduce feed-food competition more effectively than monogastric animals. Consequently, avoiding feed-food competition means that chicken production, which relies heavily on food grains, could not be sustained. Additionally, pig production was reduced due to limited feed availability, allowing egg production to be maintained at the same level as in *TrendProd* (see Supplementary Table S17). Suckler cow production was excluded from the *ChangeProd* scenario. Instead, the meat provided to the population came solely from dual-purpose dairy cattle, which also met the necessary milk production requirements.

Fig. 1 shows the distribution of biomass allocated to livestock production at the national level in the two scenarios, *MoreProd* and *ChangeProd*. The diagram illustrates the allocation streams in each scenario, with protein availability differing between them due to how biomass utilization affects the availability of other sources. In the *ChangeProd* scenario, grains and legumes suitable for direct human consumption are prioritized for food use, with 57 % of grains and 100 % of legumes allocated for human diets to satisfy protein requirements and maximize nutritional value for the population. Only the remaining portions are used for livestock feed.

The livestock diets for ruminants were designed using the Nordic feed evaluation system (NorFor; Volden, 2011) through TINE Optifor, including 3 % feeding losses for all feed types. For monogastric animals, the diet was calculated based on crude protein content, with net energy for pig and apparent metabolizable energy (nitrogen-corrected) for broilers.

2.2. LCA and sustainability indicators

The system boundaries for the environmental life cycle assessment were from cradle to farm gate for livestock production in Norway and the functional unit was 1 kg of edible protein from livestock products. The protein content in livestock products (i.e., meat, offal, milk and egg) was calculated, accounting for loss and waste in the food value chain up to the consumer (Nysted and Henriksen, 2022). The allocation principles followed PEFCR (Product Environmental Footprint Category Rules) for feed production, where economic allocation was used (FEFAC, 2018), and for dairy cattle, where biophysical allocation was used (European Dairy Association, 2018). The selected environmental indicators were climate change, land occupation, biodiversity loss, nitrogen recycling index (Tadesse et al., 2019; Møller et al., 2023), and land use ratio (van Zanten et al., 2016). For climate change, a time horizon of 100 years was

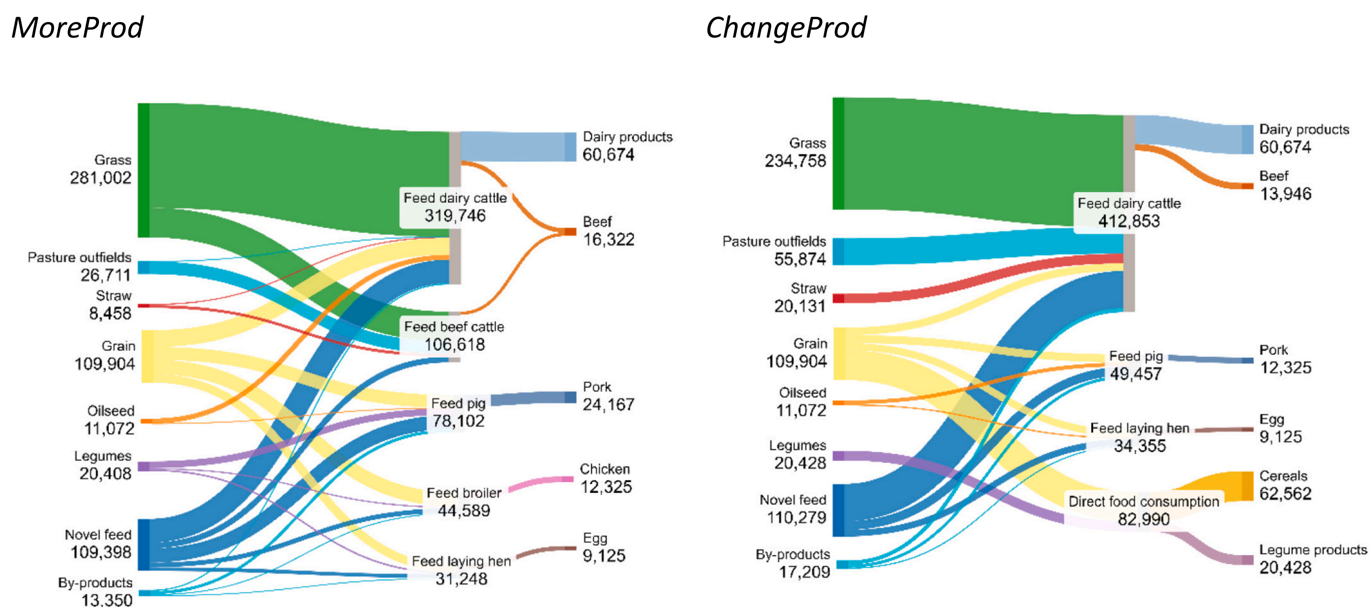

Fig. 1. Distribution of available feed resources (in tonnes of protein per year) across the two different livestock production systems, and the resulting amounts of animal products or re-directed plant-based products for human consumption in the scenarios MoreProd (left) and ChangeProd (right). 'Novel feed' refers collectively to extracted grass protein, insect protein, and yeast protein.

applied using characterization factors from the sixth assessment report (IPCC, 2021). The nitrogen recycling index (NRI) is described in Tadesse et al. (2019) and was calculated as ratio of the recycled nitrogen (NR), i. e., nitrogen in manure, as a proportion of total nitrogen which is nitrogen fertilizer and off-farm feed, as applied in Møller et al. (2023).

The biodiversity damage potential method by Knudsen et al. (2017) was used to assess the impacts on the biodiversity from land use. The potential disappeared fraction (PDF) of plant species in different spatially categorized land areas are expressed through the characterization factors which use plant species richness compared to natural conditions (i.e., forest with no management or cultivation). In this study, the PDF values per m^2 for a conventional production system according to Knudsen et al. (2019) were used. A negative value of the PDF indicates a higher plant species diversity than in the semi-natural woodland, which is the reference (Knudsen et al., 2017).

The land use ratio indicator (LUR), as described by van Zanten et al. (2016), was used to assess feed-food competition from producing feed on arable land:

$$LUR = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m}\left(LO_{ij} \times HDP\ m^{-2}y_j^{-1}\right)}{HDP\ of\ 1\ kg\ ASF}$$

LO_{ij} represents the land area utilized annually (in square meters per year) to cultivate the quantity of feed ingredient i ($i = 1$, n) in country j (j $= 1$, m) required to produce 1 kg of animal-source food (ASF), encompassing both breeding and raising of young animals. HDP_j denotes the maximum quantity of human-digestible protein (HDP) that can be generated per square meter per year through the direct cultivation of food crops in country j (country of origin). The denominator accounts for the HDP content of 1 kg of ASF.

To maintain alignment with current agricultural practices, we kept the areas designated for forage and pasture constant. This decision reflects the influence of current policy instruments in agriculture, which are subject to change over time, and the natural conditions that limit the suitability of these areas for food crop production. For imported feed ingredients and domestic concentrate ingredients, all areas were considered suitable for direct food production, and HDP was calculated using country-average yields (FAOSTAT, 2019), dry matter content, digestibility, and crude protein content for the protein crop with the highest HDP yield (e.g., wheat in Norway; van Zanten et al., 2016). The HDP from the ASF was calculated using the average protein content and the digestibility as listed by van Zanten et al. (2016).

3. Results

To evaluate the scenarios' ability to supply the Norwegian population with animal-sourced protein in 2040, the amount of protein from selected livestock products was calculated and compared to the recommended intake levels for each product category, as defined by the Nordic Nutrition Recommendations (NNR, 2023) (Fig. 2). All scenarios, within their respective limits of available bioresources for feed and food, can collectively produce annual volumes that comfortably meet the maximum recommended intake of animal-source protein for the projected population. However, when looking at individual product groups, there is an overproduction of protein from eggs, milk, pork, and beef, while chicken protein is underproduced relative to the recommended intake (NNR, 2023). The *ChangeProd* scenario, which avoids feed-food competition, yields the lowest total production of animal protein but still results in a 19 % surplus compared to NNR recommendations. This indicates that even under a circular, food-prioritizing approach, livestock production in Norway could remain sufficient to meet dietary recommendations, albeit at lower consumption levels than in the *TrendProd* and *MoreProd* scenarios. While all scenarios exceed the recommended intake levels, the *TrendProd* and *MoreProd* scenarios show a substantially greater surplus, reflecting current consumption patterns that are well above dietary guidelines.

Fig. 3 illustrates the GHG emissions, measured in kg CO_2-eq per kg protein for each livestock product (bar chart) and the distribution of GHGs (wheel chart to the right). Compared to the *TrendProd* scenario, the *MoreProd* scenario results in a slightly lower climate impact per kg protein in food, primarily due to the lower pork and broiler production resulting from the feed allocation. In contrast, the *ChangeProd* scenario has a higher climate impact of >5 kg CO_2-eq per kg protein, compared to the other two scenarios. This is attributed to the combined milk and dairy beef production in the *ChangeProd* scenario, which relies on a more extensive system with lower productivity per animal and longer rearing periods, resulting in higher impacts per unit of output despite lower total livestock units. Additionally, the feed composition in the *ChangeProd*

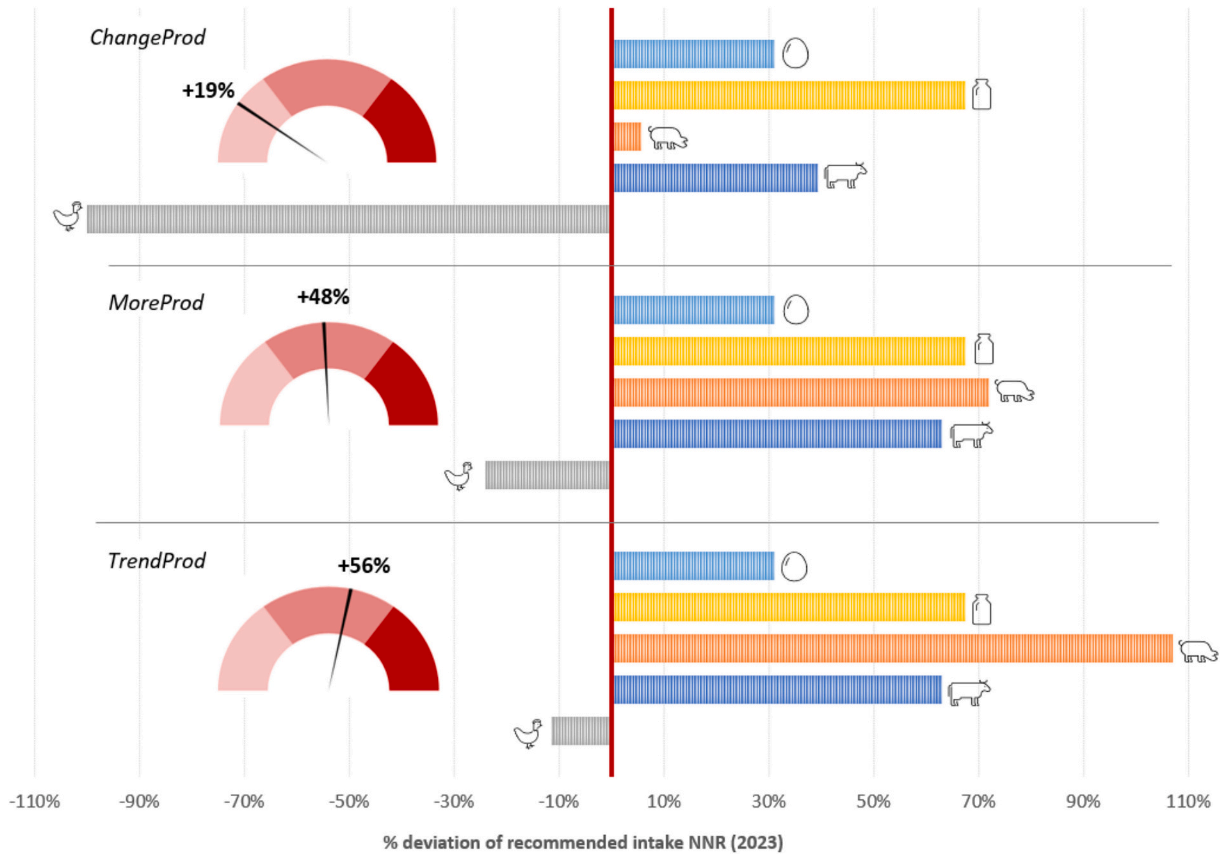

Fig. 2. The red scale (left) shows the total protein overproduction as a percentage deviation from NNR (2023) recommendations. The bars represent the percentage deviation in animal-source protein production (eggs, milk, pork, beef, and chicken) relative to the recommended intake (NNR, 2023) for the Norwegian population in 2040 (SSB, 2020) across the three scenarios: TrendProd, MoreProd, and ChangeProd. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

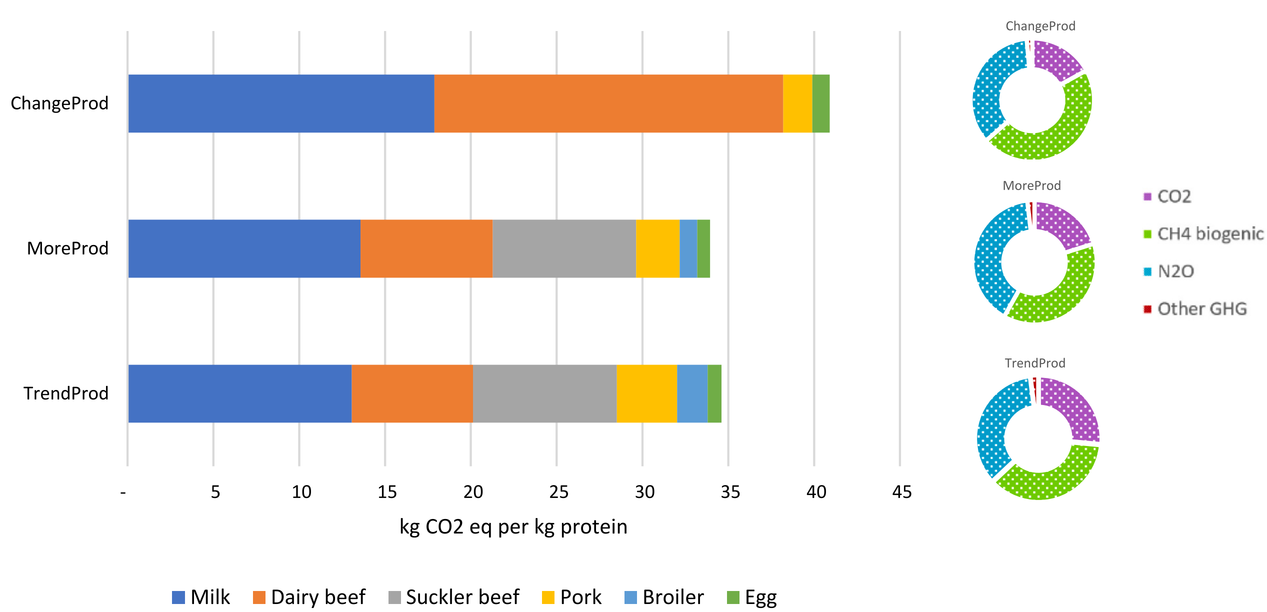

Fig. 3. GHG emissions (kg CO_2-eq per kg of animal-source protein) for the three scenarios: TrendProd, MoreProd, and ChangeProd. The results are shown by livestock products (milk, dairy beef, suckler beef, pork, broiler, and eggs) and, on the right, by the composition of greenhouse gases: carbon dioxide (CO_2), biogenic methane (CH_4), nitrous oxide (N_2O), and other gases.

scenario, which includes a larger share of low-quality feed, leads to increased methane emissions from enteric fermentation due to lower digestibility. Examining the composition of different GHG emissions within each scenario, both *MoreProd* and *ChangeProd* have a smaller share of carbon dioxide than *TrendProd*. However, *MoreProd* has a larger share of nitrous oxide, while *ChangeProd* has a larger share of biogenic methane compared to *TrendProd*. Because total protein output differs among scenarios, the total GHG emissions (CO_2-eq, without soil-carbon sequestration as reliable, system-specific data were unavailable) from the three scenarios (not shown), was 4,905,321 metric tons CO_2-eq for *TrendProd*, 4,537,083 metric tons CO_2-eq for *MoreProd*, and 4,326,027 metric tons CO_2-eq for *ChangeProd*. Compared to the baseline from 2017 (5,122,361 metric tons CO_2-eq), the potential reduction here would be up to 15,5 % if addressing the feed-food competition. Beware of that inclusion of soil-carbon dynamics could alter the absolute values.

Per kg animal-source protein, the *MoreProd* scenario uses approximately 50 % more land than the *TrendProd*, due to the increased use of outfield pasture (Fig. 4). And although less use of annual crops for the livestock production in the *ChangeProd* scenario, the land occupation is twice as high as in the *TrendProd* due to the increased use of outfields and permanent pastures. However, there is a big difference in which types of land occupation, how intensive the use is and thus also what impact it has for the environment.

For the potential loss of biodiversity, the situation is reversed. In this case, The *ChangeProd* scenario has a negative total Potential Disappeared Fraction (PDF), suggesting a positive impact on biodiversity. This improvement is attributed to the scenario's production assumptions, which promote increased use of outfields and permanent pastures, supporting more diverse ecosystems (Fig. 5). The impact on biodiversity in the *MoreProd* scenario is lower compared to *TrendProd*, accounting for about one third of the impact from *TrendProd*.

Table 2 presents the land use efficiency through the land use ratio (LUR) and approximates the circularity of the scenarios using the nitrogen recycling index (NRI). The *TrendProd* scenario has a LUR of 1.5, indicating that the land used for feed production would be more efficiently used for growing human-edible food directly. The *ChangeProd* scenario has a LUR of 0.55, demonstrating a high land use efficiency by utilizing areas not suitable for direct food production for livestock feed. The *MoreProd* scenario has a LUR around 1, meaning that land use efficiency is the same whether land is used for feed production for livestock or land is used direct for food production. NRI is used here to indicate the recycling of nitrogen within the system; a higher NRI suggests a lower risk of nitrogen pollution due to better nitrogen management practices. The *ChangeProd* scenario has the highest NRI at 0.6, followed by *MoreProd* at 0.56, both of which are higher than the *TrendProd* scenario at 0.47. This improvement is attributed to lower consumption of mineral fertilizer.

4. Discussion

4.1. Livestock strategies in the context of limited arable land

In this study, we explored three strategies for utilizing biomass in future livestock production in a country with very small share of arable land. With such land constraints, food supply stability and resilience are particularly vulnerable to external factors. Livestock can play a key role in stabilizing the domestic food supply, especially when utilizing resources unsuitable for direct human consumption. In northern latitudes, however, the risk of feed-food competition within livestock systems remains high due to short growing seasons and the need for high-quality winter feed. This competition refers specifically to the use of human-edible crops (e.g., cereals, legumes) and arable land for livestock feed rather than direct food production. These challenges are clearly illustrated in the *TrendProd* scenario. Our study did not assess future changes in crop yields or feed availability due to climate change, except for adjusting the amount of mineral fertilizer and manure used. The unpredictable effects of climate change could either enhance or deteriorate plant growth conditions, influencing the feasibility of cultivating new crop species (Heinz et al., 2024).

A significant assumption was the analysis of livestock production as if it were an isolated system, without accounting for other protein sources in the Norwegian diet, such as cereals, legumes, and fish. Although not included in the model, it is important to highlight that the fish farming industry also relies heavily on imported feed, which increases systemic vulnerability. This dependency may escalate pressure on domestic biomass, especially considering national goals for increased self-sufficiency and preparedness, which require greater reliance on domestic resources. While fish is often promoted as a key protein source, its role in the Norwegian diet is relatively limited. Over the past 20 years, fish has accounted for only around 3 % of the total per capita food supply (NIBIO, 2024). At the same time, domestic salmon production makes up approximately 70 % of Norway's total seafood exports, with nearly 80 % of all produced salmon being exported (Norwegian Seafood Council, 2024). Consequently, the contribution of fish to national food security remains limited, and increased competition for domestic biomass may further reduce the availability of plant-based foods for human consumption.

The total production volume varied across the three scenarios. While the *TrendProd* and *MoreProd* scenarios followed baseline production trends, the *ChangeProd* scenario was constrained by both the natural limits of available bioresources and the modelling choice to maintain per capita milk production. This resulted in lower overall output of animal-source food for human consumption when relying solely on domestic production. Comparing scenarios solely based on a functional unit of 1 kg of edible protein from livestock products omits the critical context of consumption volume, feed allocation priorities, and total system emissions.

Low self-sufficiency in food production makes food access heavily dependent on economic capacity and foreign supply, which can give supplier countries leverage, potentially creating imbalances in power

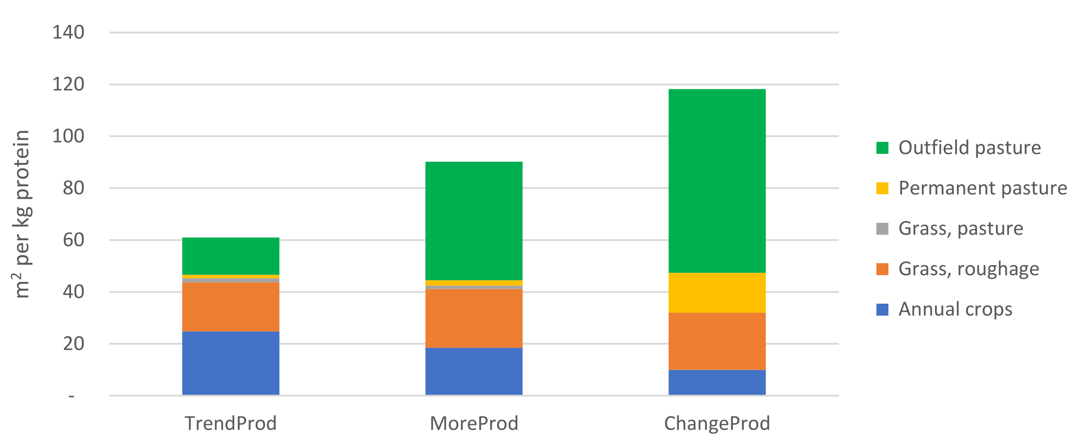

Fig. 4. Total land occupation (m^2) per kg of animal-source protein produced in the three scenarios: TrendProd, MoreProd, and ChangeProd, broken down into five land categories: outfield pasture, permanent pasture, grass in rotation for pasture, grass in rotation for roughage, and annual crops.

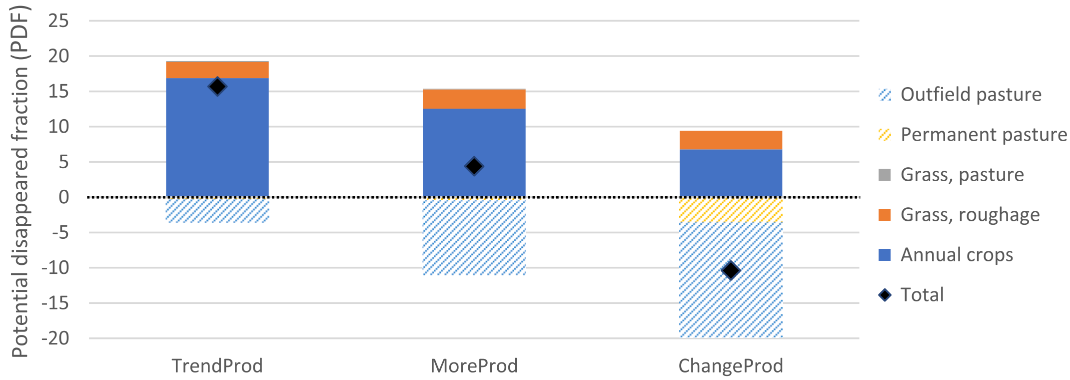

Fig. 5. Potential loss of biodiversity, expressed as Potential Disappeared Fraction (PDF) per kg of animal-source protein produced, is shown for five land categories: outfield pasture, permanent pasture, grass in rotation for pasture, grass in rotation for roughage, and annual crops. Negative values indicate increased biodiversity.

Table 2
Land Use Ratio (LUR) and Nitrogen Recycling Index (NRI) per kg of animal-source protein for livestock production in the three scenarios: TrendProd, MoreProd, and ChangeProd. NRI is defined as the share of nitrogen in manure relative to the total nitrogen input, including fertilizer and off-farm feed.

	TrendProd	*MoreProd*	*ChangeProd*
Land Use Ratio (LUR)	1.50	1.01	0.55
N in manure (kg N/kg protein)	3.3	3.9	3.8
Total N (input and manure) (kg N/kg protein)	7.0	6.9	6.3
Nitrogen recycling index (NRI)	0.47	0.56	0.60

dynamics (e.g., Henderson, 2022). A system approach to environmental impact limited to include livestock production can also be criticized for overlooking the significant role of consumption patterns in contributing to environmental impact. Adopting a broader perspective would have been essential to evaluate potential outcomes for achieving a more sustainable diet. Nonetheless, the study highlights the differing outcomes that emerge when prioritizing various societal goals in shaping the future development strategies of the livestock sector. These contrasting approaches and their implications will be explored further in the following sections.

4.2. Efficiency versus sufficiency in environmental performance

In addition to increase resilience of the food system and reduce GHG emissions, the Norwegian government has set a goal to increase the share of domestic feed ingredients (Norwegian Ministry of Education and Research, 2022). These goals challenges both production capacity, environmental impacts, and the efficiency in use of biomass in the livestock sector. Efficient production systems generally have a lower environmental impact in terms of climate change compared to more extensive systems when evaluating the impact per product unit (e.g., Haas et al., 2001; Chiriacò et al., 2022; Bronts et al., 2023). In this study, both the *TrendProd* and *MoreProd* scenarios emphasize production efficiency. When comparing GHG emissions per kg of animal-source protein produced, these scenarios have 15 % and 17 % lower emissions, respectively, compared to the *ChangeProd* scenario. Increased productivity is awarded when the traditional GWP_{100} calculation method is applied, using 100-year global warming potential characterization factors from the IPCC Sixth Assessment Report (AR6) to express emissions in CO_2-equivalents, as also pointed out by Samsonstuen et al. (2023). However, in the *ChangeProd* scenario, the composition of greenhouse gases changes, with an increase in biogenic methane and a decrease in carbon dioxide. Methane is a potent but short-lived climate pollutant. From a long-term perspective, an extensive livestock production system could still be favoured (Samsonstuen et al., 2023). When examining the total GHG emissions of our chosen livestock production systems, the most extensive system (*ChangeProd*) had the lowest impact due to its reduced production levels. A systems perspective is essential for determining future strategies, as long-term policy decisions must consider local conditions, nutritional needs, and environmental risks (Beal et al., 2023). This also includes considering the distributional effects of structural change. In the Norwegian context, large parts of the country depend on ruminant production to maintain agricultural activity on marginal land. Therefore, any transformation must balance environmental goals with the need to sustain rural livelihoods and national food security. In this sense, the ChangeProd scenario illustrates how a sufficiency-based pathway can reduce environmental impact while maintaining a geographically distributed food system, contributing to a more equitable transition for stakeholders within Norwegian agriculture (Herzon et al., 2023).

Animals grazing on outfields and permanent pastures positively impact local ecosystems in several ways. Firstly, their presence contributes to maintaining open landscapes, which can enhance sunlight reflection and potentially moderate atmospheric warming (Finne et al., 2023). Grazing also enhances biodiversity by influencing vegetation structure and aiding seed dispersal, leading to a rich variety of plant life (Cederberg et al., 2018; Klimek et al., 2007; Oldén et al., 2016). Moreover, plant growth benefits from the nutrients returned to the soil through animal feces, which also boosts microbial activity (Barreiro et al., 2022). Responsible grazing practices mimic natural disturbances like wildfires, promoting new growth (Schippers et al., 2014). Both alternative scenarios to the trend projection suggest increasing the share of grazing. However, only the *ChangeProd* scenario and the approach of using livestock as recyclers lead to a net gain in biodiversity.

4.3. Alignment with nutritional needs and dietary shifts

Our study demonstrated that relying solely on domestic biomass resources for livestock production in Norway (as modeled in the *MoreProd* and *ChangeProd* scenarios) can ensure sufficient production of animal-source foods (ASF) to meet the population's maximum recommended dietary protein intake within each separate food category by 2040, according to the Nordic Nutrition Recommendations (NNR, 2023). This was valid for all livestock products except chicken. In the *TrendProd* scenario, chicken production was based on the projected per capita production of the baseline year 2017, which was lower than the maximum recommended intake (NNR, 2023). The *MoreProd* scenario used the same basis, resulting in an apparent underproduction of chicken compared to the dietary guidelines in both these scenarios. In the *ChangeProd* scenario, the conversion of low-value biomass was prioritized, so chicken was not given priority in the feed allocation hierarchy. Neither was the suckler cow production, as the dual-purposed production could provide both milk and meat, as also reported in other studies (e.g., van Selm et al., 2023).

A study with a circular redesign of a European food system, resulted in a reduction of 44 % in land use compared with the current food system (Simon et al., 2024). The avoidance of feed-food competition in livestock production under the *ChangeProd* scenario did not reduce land use per kg animal-sourced protein, due to increased use of outfield pastures and permanent pastures, but the scenario rather reduced feed-food competition substantially and imposed a natural ceiling on the production volume of ASF due to the limited availability of feed resources. This constraint will necessitate a dietary shift by reducing per capita intake of ASF unless meat imports are increased to compensate for the shortfall. It is well established that food consumption impacts human health, and dietary recommendations in developed countries increasingly emphasize more plant-based foods and less ASF, especially red meat (e.g., NNR, 2023). The reduced use of arable land for livestock feed led to an equivalent increase in the production volume of cereals and legumes for direct human consumption. However, the study did not account for the potential to increase crop production beyond changes in how arable land is utilized, such as shifts in the types of crops being grown, but a recent study from Norway showed that it is possible to increase the production of peas, faba beans, rapeseed and turnip rapeseed (Svanes et al., 2024).

4.4. Aligning livestock production with dietary recommendations

Achieving environmental sustainability requires both efficiency (reducing environmental impact per unit of functionality) and sufficiency (reducing impact through lower or altered functionality) (André, 2024; Herzon et al., 2024). Current Norwegian diets exceed recommended intake levels for red meat and total animal-source protein, while under-consuming plant-based protein sources such as legumes (Directorate of health, 2023). The *TrendProd* and *MoreProd* scenarios mirror current consumption patterns and thus reflect substantial overproduction, reinforcing the issue of overconsumption. In contrast, the *ChangeProd* scenario emphasizes ruminant-based production and results in a lower total output of animal-source protein, aligning more closely with nutritional recommendations in terms of quantity, but not composition. It challenges prevailing dietary guidelines that promote higher intake of white over red meat, as it overproduces red meat while reducing poultry and potentially milk supply. These shifts imply a dietary change toward greater reliance of ruminant products from dual-purpose dairy systems, accompanied by increased consumption of plant-based food. While this deviates from conventional health recommendations and consumer preferences, it represents a sufficiency-based strategy optimized for domestic biomass use and reduced feed-food competition. A combined sufficiency-efficiency approach may therefore offer the most realistic potential for sustainable food system transformation in land-constrained contexts like Norway (André, 2024). In *ChangeProd*, aligning production with the efficient use of domestic feed resources implies a reduction in poultry and potentially milk intake compared to today. Instead, the diet would rely more on ruminant products from dual-purpose dairy systems, complemented by increased consumption of plant-based foods. While this deviates from conventional dietary advice, it represents a coherent strategy for optimizing the use of limited arable land and minimizing feed-food competition.

4.5. Limitations and implementation challenges

The exclusion of critical impact categories, such as ecotoxicity and soil quality, limits the comprehensiveness of the environmental assessment. Ecotoxicity, which reflects the environmental harm caused by pesticide use, was omitted due to insufficient Norwegian-specific data. However, its inclusion would be essential for differentiating between production systems, as those using fewer or no chemicals might otherwise not receive appropriate recognition for their lower impacts. Similarly, soil quality, particularly the role of soil organic carbon (SOC), was excluded due to methodological uncertainties and data gaps. This omission may overlook important benefits linked to improved manure use and crop rotation, especially in scenarios like *ChangeProd*.

These findings remain theoretical and highlight significant practical challenges that must be addressed before they can inform governmental strategies. Farmers may face increased costs, market fluctuations could impact rural economies, and resistance to changing dietary habits may arise. In addition, spatial considerations—such as the geographic distribution of arable land, transport logistics for biomass and by-products, location of processing infrastructure, and seasonal storage needs may significantly influence the feasibility and environmental performance of each scenario. These factors are particularly relevant for implementing circular systems such as *ChangeProd*. Supplementary Tables S3-S6 provides regional data on biomass availability that could support such spatial analyses. Moreover, structural changes at the farm level may be required, such as transitioning from monogastric to ruminant-based systems, which would involve changes in infrastructure, knowledge, and market orientation. As discussed by Lyng et al. (2024), realizing a biomass value hierarchy in practice requires not only reconfiguring production systems but also aligning economic incentives, policy frameworks, and logistics to support the use of low-opportunity-cost biomass. Current support schemes are largely designed around existing production structures and may need to be revised to enable this transformation. To overcome these barriers and uncertainties, further research is needed, including pilot programs to test the proposed changes in real-world settings.

5. Conclusion

The changes proposed in the *ChangeProd* scenario would enhance biodiversity and significantly reduce feed-food competition, improving the resource efficiency of Norway's livestock production system. By prioritizing outfield pasture and avoiding feed-food competition, it is possible to produce sufficient animal-source food to meet the population's nutritional needs – though not necessarily its current preferences. Although this may contrast with consumer habits and dietary advice promoting white over red meat, the scenario demonstrates that aligning production with domestic biomass availability can support a lower-impact food system while still meeting nutritional requirements. While using low-opportunity-cost biomass increases the climate impact per tonne of protein, the overall climate footprint is reduced due to lower total production. This approach benefits the environment by reducing greenhouse gas emissions and fostering healthier ecosystems with greater species richness. Developing comprehensive policies to support sustainable practices and address community impacts is essential. The actions outlined in the *ChangeProd* scenario not only promote long-term sustainable agriculture in Norway but also offer a model for other countries aiming to balance food production with environmental sustainability.

Sample CRediT author statement.

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Disclosure statement

The authors report there are no competing interests to declare.

CRediT authorship contribution statement

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During the preparation of this work the author(s) used ChatGPT4.0 in order to improve readability and language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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