



# Net climate impacts of sustainable intensification measures in boreal Finnish crop-livestock system

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## ABSTRACT

Sustainable intensification (SI) aims to increase productivity while minimizing environmental impacts and preventing land expansion. Although SI strategies are widely promoted, their overall climate mitigation potential in boreal crop–livestock systems remains uncertain. This study quantified the impacts of potential SI options on greenhouse gas (GHG) emissions and soil organic carbon (SOC) stocks in a representative Finnish dairy system. Two SI options were evaluated: (1) increasing crop yields and (2) reducing the grain proportion in dairy cow diets. Soil carbon inputs were derived from agricultural statistics and literature data, SOC stock changes were estimated using the Yasso07 soil model, and total GHG emissions were calculated with the Carbon Calculator life cycle assessment (LCA) model over 20- and 100-year horizons. Livestock processes accounted for the largest share of GHG emissions, while SOC-related emissions were mainly driven by organic soil cultivation. SI options that reduced land use for feed production, particularly on organic soils, achieved up to 38% lower total climate impact compared with the baseline. Including SOC stock changes increased total LCA-based emissions by up to 30%, emphasizing the importance of soil processes in mitigation assessments. The findings demonstrate that targeted SI strategies integrating productivity-enhancing and emission-reducing measures can effectively improve the climate performance of boreal dairy systems, supporting the transition toward carbon-neutral and climate-smart agriculture.

## 1. Introduction

Agriculture is at the heart of the sustainability challenge. It is the single largest driver of global environmental change (Crippa et al., 2021; Davis et al., 2016; Tilman et al., 2011), and is at the same time highly vulnerable to these changes (IPCC, 2022). A shift towards sustainable agricultural intensification (SI), including the adoption of climate-smart agriculture (CSA), is essential. CSA aims to increase productivity, enhance climate resilience and reduce environmental impacts (Lipper et al., 2010). This aligns with the broader goal of ensuring food security while maintaining the sustainability of the Earth system (Richardson et al., 2023). Addressing sustainability requires action at all levels, from farms to nations (Folke et al., 2005). Comprehensive evaluations of practical solutions are crucial for tailoring climate mitigation strategies

to specific farming systems and regional conditions.

Over the past five decades, dairy production has expanded rapidly (FAO, 2018). While productivity has increased, the environmental impacts have grown, ranging from GHG emissions and eutrophication to biodiversity loss and animal welfare concerns (Del Prado et al., 2013; Herzog et al., 2018; Westhoek et al., 2014). In boreal regions, dairy production is strongly based on crop–livestock integration and a high reliance on perennial forage crops, which play a key role in both productivity and environmental performance. In Finland, agriculture accounts for approximately 28% of total GHG emissions, including the LULUCF sector (Statistics Finland, 2024). Key emission sources in dairy farming include methane from enteric fermentation and manure, nitrous oxide from fertilized soils, and carbon dioxide from organic soils (Bianchi et al., 2021; Kekkonen et al., 2019; Wang et al., 2021).

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Reducing agricultural emissions is essential to meet both global targets under the Paris Agreement (Roe et al., 2019) and Finland's national goal of climate neutrality by 2035 (Government of Finland, 2019). Mitigation efforts focused on organic soils are particularly important in boreal systems, as these soils contribute over 50% of agricultural GHGs while covering only 11% of cultivated land (Kekkonen et al., 2019).

Much of the current SI research focuses on increasing crop yields (Mueller et al., 2012; Palosuo et al., 2021). In boreal cropping systems, promising practices include improved crop rotations, liming, better drainage, sowing techniques, and high-yield forage mixtures (Lehtonen et al., 2018). Adjusting cattle diets to increase the roughage share can also intensify field use and reduce land needs, as grass has roughly double the yield potential of grain in Finland (Tzemi and Lehtonen, 2022). This could spare land for alternative uses, such as green fallows that boost soil organic carbon (SOC) through high biomass production. However, changes in feeding strategies may also affect animal productivity and feed efficiency, highlighting the need for system-level assessments that consider both agronomic and livestock-related effects.

Life Cycle Assessment (LCA) is a commonly used method to assess environmental impacts of agricultural systems, including GHG emissions. However, it often excludes SOC changes due to methodological uncertainties (Bessou et al., 2020; Goglio et al., 2015; Hashemi et al., 2024; Joensuu et al., 2021). This omission can be particularly problematic in boreal systems, where soil carbon dynamics, especially on organic soils, strongly influence the overall climate impact of agricultural production (Lehtilä et al. 2025). For instance, Knudsen et al. (2019) reported up to 18% reduction in milk's climate impact when SOC was accounted for using the Danish method (Petersen et al., 2013).

Despite growing interest in SI, few studies have quantified its combined effects on GHG emissions and SOC stocks in integrated crop–livestock systems under boreal conditions. Previous research has typically examined either productivity or environmental outcomes in isolation, leaving uncertainties about system-level trade-offs and synergies. In particular, the net climate mitigation potential of combining yield improvements and dietary modifications remains insufficiently understood in boreal dairy systems.

The objective of this study was to quantify the net climate impacts of selected SI strategies in a representative boreal dairy system in Finland. Specifically, we evaluated two SI options: (1) increasing crop yields through improved soil and crop management, and (2) reducing the grain proportion in dairy cow diets in favour of forage. In this study, climate impacts are understood as changes in greenhouse gas (GHG) emissions and soil carbon dynamics. Using a combined soil carbon model (Yasso07) and life cycle assessment (LCA) approach, we evaluated their impacts on GHG emissions and SOC stocks at both farm and product (milk) levels over 20- and 100-year time horizons. The analysis focused on management-driven differences between scenarios, while climatic conditions were considered unchanged to isolate the effects of sustainable intensification measures.

The study addresses the following research questions:

- (i) How do yield improvement and dietary modification affect soil carbon inputs and SOC stock changes in boreal crop-livestock systems?
- (ii) What is the net effect of these SI strategies on total GHG emissions when SOC dynamics are included?
- (iii) How do climate impacts differ when assessed at farm, product, and area-based functional units?

By addressing these questions, the study aims to support the design of climate mitigation strategies that are both agronomically feasible and environmentally effective in northern crop-livestock systems.

## 2. Materials and methods

### 2.1. Study area and case farm description

Dairy production is the most important agricultural sector and rural livelihood in northern Europe, accounting for 50% of the agricultural gross return in Finland (Virkejärvi et al., 2015). This study focuses on a representative boreal dairy production system located in North Savo, eastern Finland, which is one of the country's most significant dairy production regions. In 2022, North Savo produced approximately 14% of Finland's total milk output (OSF, 2025).

Finnish dairy farms are typically family-owned and characterized by relatively high milk yields and strong reliance on forage-based feeding. In 2022, the average farm size was 52 ha, with an average herd size of 52 cows and an average milk yield of 8 673 kg per cow (OSF, 2025), which is above the EU average of 7 653 kg (EUROSTAT, 2025). The concentrate rate in the dairy cow diets is typically around 45%, with forage accounting for the remaining share of the dry matter intake (Huhtamäki, 2023). Organic soils cover 8% of the cultivated area in North Savo, but their share is higher on dairy farms due to the historical use of grasslands on organic soils (Kekkonen et al., 2019).

The climate impacts of SI options were analysed using a hypothetical case study farm designed to represent typical dairy production conditions in North Savo. The case farm comprised 140 dairy cows. In the baseline scenario, the total cultivated area required for fodder production was 225 ha, of which 125 ha was allocated to grasslands, 50 ha to oat, and 50 ha to barley. Of the total production area, 80% was assumed to be located on mineral soils and 20% on organic soils, with an equal crop distribution across soil types. Baseline crop yields were 7 000 kg dry matter ha<sup>-1</sup> for silage and 3 400 kg dry matter ha<sup>-1</sup> for oat and barley. Fat and protein corrected milk (FPCM) production was 10 050 kg cow<sup>-1</sup> yr<sup>-1</sup> in the baseline scenario with a 45% grain proportion and 9 394 kg cow<sup>-1</sup> yr<sup>-1</sup> in scenarios with a 30% grain proportion in the diet.

### 2.2. SI scenarios

To study the climate impacts of different SI options, we developed a set of scenarios with varying forage yield levels and proportions of concentrated feed in the diet of dairy cows (Table 1). The scenarios were designed to represent plausible management-driven changes under boreal farming conditions, rather than extreme interventions.

In Finland, the yield gap between actual and potential yields on farms is substantial. For example, in 2023 the yield gap of barley in North Savo was approximately 1 200 kg ha<sup>-1</sup>, meaning that average farm yields were considerably lower than those achieved by the most productive farms in the region (OSF, 2025). Closing this yield gap through improved soil structure, drainage, crop rotation, and nutrient management is considered a realistic sustainable intensification pathway under Finnish conditions (Lehtonen et al., 2018). Reducing the gap is important both for the economic viability of farms and

**Table 1**

Characteristics of cattle diet, crop yields and total production area in the scenarios.

Scenario	Share of concentrated feed in the diet, %	Yields	The area used in calculation
Baseline (BL)	45	Current	Total farm area
S1	45	+20%	Total farm area
S2	30	Current	Total farm area
S3	30	+20%	Total farm area
S4	45	+20%	Forage production area
S5	30	+10%	Forage production area
S6	30	+20%	Forage production area

environmental sustainability, as more efficient use of cultivated land may allow part of the production area to be released for alternative uses.

In the SI-scenarios, yield increases of 10% and 20% compared to the baseline were assumed for all cultivated crops, representing moderate improvements achievable through enhanced soil and crop management. These yield increase levels are consistent with reported yield gaps in Finnish cereal and forage production (Iivonen et al., 2024). The assumed yield improvements reflect better soil conditions achieved through crop rotation, liming, improved drainage, and optimized nutrient and water management, supported by increased farmer knowledge and advisory services.

In addition to yield improvement, dietary modification was examined as a second SI option. The grain proportion (GP) in the diet of dairy cows was reduced from 45% in the baseline to 30% in the dietary modification scenarios, reflecting increased reliance on forage crops. This adjustment is within the range of feeding strategies applied in Finnish dairy production and is consistent with national feeding recommendations (Korhonen, 2024). For all scenarios, dry matter intake was adjusted according to milk production and diet composition, resulting in 25.0 kg DM cow<sup>-1</sup> d<sup>-1</sup> for the 45% GP diet and 24.7 kg DM cow<sup>-1</sup> d<sup>-1</sup> for the 30% diet (Huhtanen et al., 2011).

In the 45% concentrate diet, the feed ration consisted of 7.7 kg DM cow<sup>-1</sup> d<sup>-1</sup> of cereal grains, 14.8 kg DM cow<sup>-1</sup> d<sup>-1</sup> of forage, and 2.5 kg DM cow<sup>-1</sup> d<sup>-1</sup> of rapeseed meal. In the 30% concentrate diet, the ration included 3.6 kg DM cow<sup>-1</sup> d<sup>-1</sup> of cereal grains, 18.5 kg DM cow<sup>-1</sup> d<sup>-1</sup> of forage, and 2.6 kg DM cow<sup>-1</sup> d<sup>-1</sup> of rapeseed meal. These feed compositions were selected to maintain nutritionally balanced diets while reflecting realistic shifts in forage-to-concentrate ratios (Kuoppala et al., 2024). Other parameters applied in the life cycle assessment are presented in Supplementary material 1.

Land area required for feed production varied among scenarios as a result of changes in crop yields and dietary composition. In the baseline and scenarios S1, S2 and S3, the total cultivated area of the farm was retained in the analysis. In scenarios S1, S2 and S3 land released from feed production due to yield improvements or dietary changes was allocated to green fallow. In contrast, scenarios S4, S5 and S6 focused on product level assessment, and the area released through SI-measures was excluded from the system boundary. In these cases, the released area was assumed to be located on organic soils, and emissions from these areas were not attributed to dairy production, allowing assessment of the climate impacts of production intensification independent of alternative land uses.

An overview of the scenario characteristics, including concentrate proportion, yield levels, and system boundaries, is presented in Table 1.

### 2.3. Description of the climate impact analysis

We used agricultural statistics and literature to estimate C inputs, the Yasso07 soil model (Tuomi et al., 2011) to quantify changes in SOC stocks in mineral soils and IPCC default emission factors to estimate SOC-related emissions from organic soils. The analysis focused on quantifying management-driven differences in climate impacts between scenarios, while climatic conditions were assumed to remain unchanged across all scenarios.

Life Cycle Assessment (LCA) was used to estimate GHG emissions from the dairy production system using the 'Carbon Calculator-model' (Tuomisto et al., 2015). The LCA covered emissions from feed crop cultivation, animal processes, manure management, energy use, and purchased inputs, but excluded land-use sector emissions related to SOC stock changes, which were quantified separately using the soil carbon modelling approach described above.

The overall climate impact of each scenario was calculated by combining LCA-based GHG emissions with annualized SOC stock changes from mineral and organic soils. SOC stock changes were converted to CO<sub>2</sub> equivalents and added to the LCA results to obtain total climate impacts at the farm and product levels. This approach allowed

consistent integration of soil carbon dynamics into the life cycle framework while avoiding double counting of soil-related emissions.

The assessment was conducted for multiple functional units, including the whole-farm, fat and protein-corrected milk (FPCM), and cultivated area (ha), depending on the scenario. System boundaries differed between scenarios to reflect alternative assumptions regarding land released through sustainable intensification measures, as described in Section 2.2. An overview of the modelling framework and system boundaries is presented in Fig. 1.

### 2.4. Estimation of the C inputs

C inputs originating from the crop production were estimated for each scenario using agricultural statistics and literature data. We estimated the C inputs allocated to soil (kg C ha<sup>-1</sup>), including above-ground biomass remaining in the field (plant residues and stubble) and below-ground C input (plant roots and root excreta) following the approach of Bolinder et al. (2012). This data was complemented with national parameter values (Palosuo et al., 2015) to convert yield data to soil C inputs. C contents of all plant components were assumed to be 0.45 (Jensen et al., 2005). Crop yields were assumed to be the same on mineral and organic soils, in line with national greenhouse gas inventory practices.

C inputs from manure (kg C ha<sup>-1</sup>) were estimated based on the number of animals and total field area in each scenario. The C content of manure was assumed to be 0.50 (Pettygrove et al., 2009). The amount of manure produced followed the national statistics: 6.12 kg dry matter head<sup>-1</sup> day<sup>-1</sup> for dairy cows, 2.2 kg for heifers, and 1.1 kg for calves under one year of age (Statistics Finland, 2024). Manure was assumed to be evenly distributed across the cultivated area within each scenario.

For each scenario, total soil C input was calculated as the sum of crop residue inputs, root-derived inputs, and manure-derived inputs, averaged over the relevant production area. The differences in soil C inputs between scenarios therefore reflect changes in crop yields, crop composition, and land use resulting from sustainable intensification measures.

### 2.5. Estimation of the changes in the SOC

SOC changes in mineral soils were estimated following the approach of Palosuo et al. (2015) using the Yasso07 soil model (Tuomi et al., 2011). The model describes the decomposition of organic matter based on information on climate and C input quality. In this study, climatic conditions were held constant across all scenarios to isolate the effects of management-driven changes in carbon inputs on SOC dynamics.

Yasso07 is currently used in the Finnish GHG inventory (Statistics Finland, 2024) and has been tested and applied in multiple studies assessing SOC dynamics in agricultural soils under Nordic conditions (Karhu et al., 2012; Riggers et al., 2019). Its use therefore ensures consistency with national reporting practices and comparability with previous studies.

The model requires information on the C input quality in AWENs fractions which describe the chemical composition of organic materials as acid (A), water (W), ethanol (E) soluble, and non-soluble (Ns) fractions. Here, we used AWENs fractions of crops and manure presented by Palosuo et al. (2015). The shares of cultivated crops relative to the total production area (scenarios BL, S1, S2, S3) or forage production area (S4, S5, S6) were calculated (Table 1), and together with the estimated manure inputs, were used to derive average annual soil C input rates (kg C ha<sup>-1</sup> yr<sup>-1</sup>) for each scenario.

Climatic data was obtained from the Finnish Meteorological Institute, as described by Palosuo et al. (2015), representing the average of the selected region during the time period 1961–2018. The climate variables used were annual precipitation (mm), annual mean temperature (°C) and the annual temperature amplitude (°C) which describes intra-annual variation in temperature.

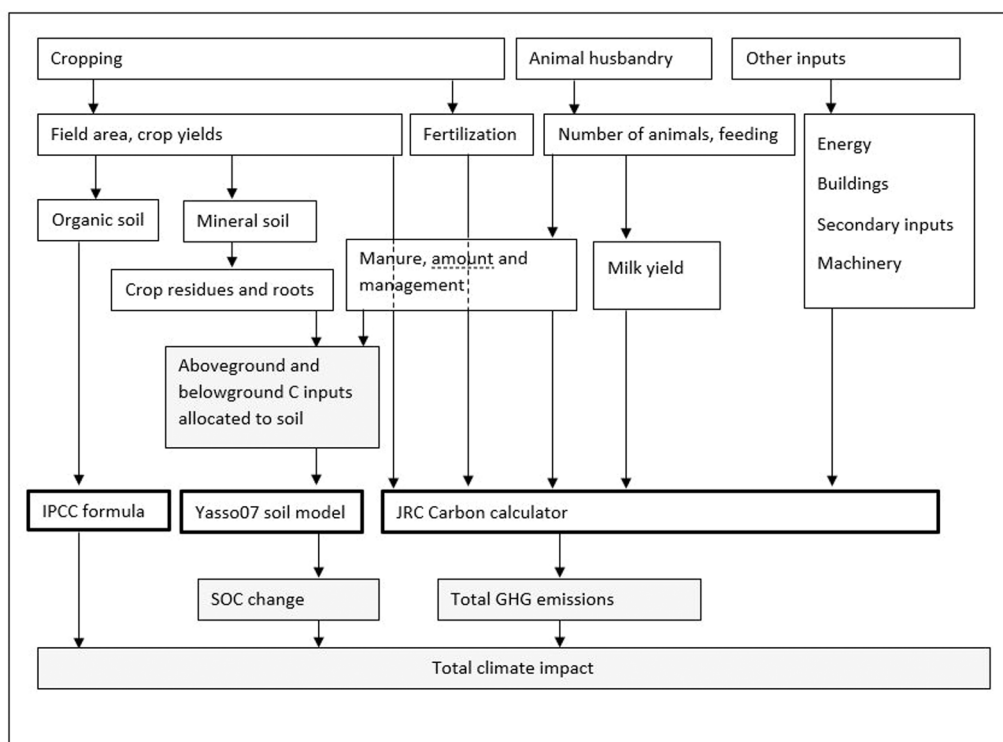


Fig. 1. Description of the examined processes and models used in the study. Different methods are indicated by thick black borders, and study outputs are shown in gray.

SOC stocks under the baseline scenario were assumed to represent steady-state conditions corresponding to current farming practices. The steady-state SOC stock of the baseline scenario was therefore used as the initial condition for all scenario simulations. Changes in SOC stocks in the SI scenarios were calculated as the mean difference between simulated annual stocks of each scenario and the baseline.

SOC stock changes were simulated over 20-year and 100-year time horizons. SOC stock changes were simulated over a 100-year time horizon for integration into the life cycle assessment, in line with IPCC guidelines and standard climate impact assessment practices (Knudsen et al., 2019). Although the Product Environmental Footprint Category Rules (PEFCR) for dairy products recommend a 20-year time horizon (EDA, 2018; European Commission, 2021), the 100-year period was selected to ensure consistency with global warming potential metrics and to provide a robust estimate of long-term soil carbon dynamics. Results for a 20-year time horizon are additionally reported to illustrate shorter-term SOC responses. Based on the simulated SOC stock changes, average annual SOC change rates were calculated and converted to carbon dioxide equivalents using the molecular weight ratio of CO<sub>2</sub> to carbon (3.67).

As the Yasso07 model is applicable only to mineral soils, SOC changes in organic soils were estimated using IPCC default emission factors, following the approach applied in the Finnish national greenhouse gas inventory (Statistics Finland, 2024). Emission factors of 28 967 kg CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> for cereals and 20 900 kg CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> for grasses were used to represent emissions from cultivated organic soils. These hectare-based emissions were consistently included in all scenarios according to their land-use on organic soils.

For scenarios S1, S2 and S3, the released area was assumed to be allocated to green fallow. Carbon inputs to soil from green fallow were estimated assuming that all above-ground biomass was returned to the soil. Total farm-level SOC change was calculated as the sum of SOC changes from mineral soils and SOC-related emissions from organic soils.

## 2.6. Estimation of the total life cycle GHG emissions

Total life cycle GHG emissions were estimated using the Carbon Calculator life cycle assessment (LCA) model (Tuomisto et al., 2015). The analysis quantified GHG emissions associated with the dairy production system at both whole-farm and product levels. The LCA focused on emissions from agricultural production processes and excluded soil organic carbon (SOC) stock changes, which were quantified separately as described in Section 2.5 and integrated afterwards to follow more closely the approach of the national GHG inventory.

The Carbon Calculator model was supplemented with a model for estimating methane emissions from enteric fermentation developed by Ramin and Huhtanen (2013). This model is widely used in Finnish cattle LCA studies (Hietala et al., 2021; Huuskonen et al., 2023) and is specifically parameterized for Nordic feeding conditions, providing more detailed estimates of enteric methane emissions than the default IPCC Tier 2 approach (IPCC, 2006). The model requires detailed information on diet composition and feed quality, which were specified according to the scenario descriptions in Section 2.2.

Allocation between milk and meat production was performed using the International Dairy Federation biophysical allocation method (IDF, 2015), as recommended by the Product Environmental Footprint Category Rules (PEFCR) for dairy products (EDA, 2018). This allocation approach reflects the physiological relationship between milk and meat production and is commonly applied in European dairy LCAs.

Characterisation factors for global warming potential (GWP) were based on the IPCC 5th Assessment Report, with values of 1 for CO<sub>2</sub>, 298 for N<sub>2</sub>O (including climate-carbon feedback), and 34 for biogenic CH<sub>4</sub>. The system boundary was defined from cradle to farm gate. Included life cycle stages were feed crop cultivation, animal processes (enteric fermentation and manure management), purchased inputs, on-farm energy use, and buildings and machinery.

Depending on the scenario, the system boundary included either the total farm area (baseline and scenarios S1, S2 and S3, the latter three including fallow) or only the feed crop cultivation area related to dairy

production (scenarios S4, S5 and S6). These alternative system boundaries were used to assess the influence of land-use allocation assumptions on the estimated GHG emissions.

Total life cycle GHG emissions including soil carbon effects were calculated by combining LCA-based emissions with SOC-related emissions and removals as:

$$GHG_{\text{total}} = GHG_{\text{LCA}} + GHG_{\text{SOC}}$$

where  $GHG_{\text{LCA}}$  represents life cycle GHG emissions estimated using the Carbon Calculator (excluding soil carbon stock changes), and  $GHG_{\text{SOC}}$  represents annualized SOC stock changes in mineral soils and  $\text{CO}_2$  emissions from cultivated organic soils, expressed in  $\text{CO}_2$  equivalents. The integration of SOC stock changes and LCA-based emissions is illustrated in Fig. 2.

GHG emissions were calculated for three functional units: the whole-farm (annual emissions), 1 000 kg fat- and protein-corrected milk (FPCM), and cultivated area (ha). These functional units were selected to allow assessment of climate impacts from farm-level, product-level, and land-use efficiency perspectives.

### 2.7. Uncertainty considerations

The results are based on scenario simulations combining a soil model and a life cycle assessment framework. As with all model-based assessments, uncertainties arise, in addition to the model structures, from input data, emission factors, and assumptions regarding management practices. In this study, key sources of uncertainty include assumptions on crop yield changes due to intensification, estimates of soil carbon inputs, emission factors for organic soils, and parameters related to enteric methane emissions.

A full quantitative uncertainty analysis was not conducted. Instead, uncertainty was addressed through a scenario-based approach in which key management-related parameters, namely crop yield levels, concentrate proportion in dairy cow diets, and land-use allocation, were systematically varied to capture a plausible range of outcomes. This approach allows assessment of the relative magnitude and direction of changes in greenhouse gas emissions and soil organic carbon stocks between scenarios, rather than precise absolute estimates.

Uncertainties related to soil organic carbon dynamics are particularly relevant, given the long response times of soil systems and the simplified representation of organic soils using IPCC default emission factors. However, the use of nationally applied methods and parameters, including the Yasso07 soil model and inventory-based emission factors,

ensures consistency with existing reporting frameworks and supports the robustness of relative comparisons between scenarios.

While uncertainties affect the absolute magnitude of estimated climate impacts, the comparative nature of the scenario analysis provides confidence in the main conclusions regarding the relative climate mitigation potential of different sustainable intensification practices.

## 3. Results

### 3.1. Impacts of SI scenarios on carbon inputs into soil

Hectare-based carbon inputs into soil increased in all SI scenarios. The average total C input into the soil varied between 2.4 and 3.8  $\text{Mg C ha}^{-1} \text{ yr}^{-1}$  in different SI scenarios (Fig. 3). This value is derived from current crop residues, root biomass and root excreta contributions under existing management practices (Table 2, Supplementary Figure S1). In the scenarios where yield increases were achieved through improved soil growing conditions, C inputs into the soil varied between 2.6 and 3.8  $\text{Mg C ha}^{-1} \text{ yr}^{-1}$  (Fig. 3). The scenario involving a decreased, 30% grain proportion in the diet of dairy cows (S2), showed a 19% increase in the average C inputs into the soil, compared to the baseline value. These differences in soil carbon inputs reflect management-driven changes in crop yields, crop composition and land allocation between scenarios.

### 3.2. Impacts of SI scenarios on soil organic carbon stocks and soil-related GHG emissions

All SI scenarios resulted in an increase in mineral SOC stocks. The increase in SOC stocks varied between 2.1 and 12.8  $\text{Mg C ha}^{-1}$  over the 100-year simulation period and between 0.9 and 5.8  $\text{Mg C ha}^{-1}$  over the 20-year simulation period (Fig. 4). The annual change in SOC ranged from 0.02 to 0.13  $\text{Mg C ha}^{-1} \text{ yr}^{-1}$  over the 100-year simulation period and between 0.05 and 0.29  $\text{Mg C ha}^{-1} \text{ yr}^{-1}$  in the 20-year simulation period (Fig. 5). Total soil-related GHG emissions (including mineral SOC changes and emissions from organic soils) varied between scenarios, depending largely on the assumptions made regarding the area released through the implementation of SI options. Total soil-related GHG emissions, including mineral SOC changes and  $\text{CO}_2$  emissions from organic soils, varied between scenarios and ranged from 1102 to  $-26 \text{ Mg CO}_2 \text{ yr}^{-1}$  (Fig. 6).

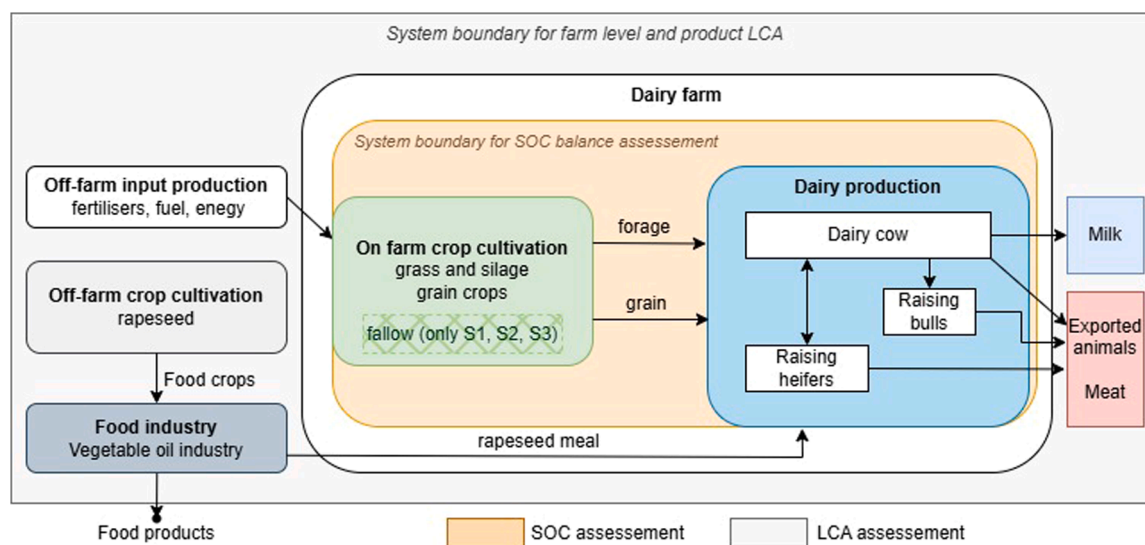
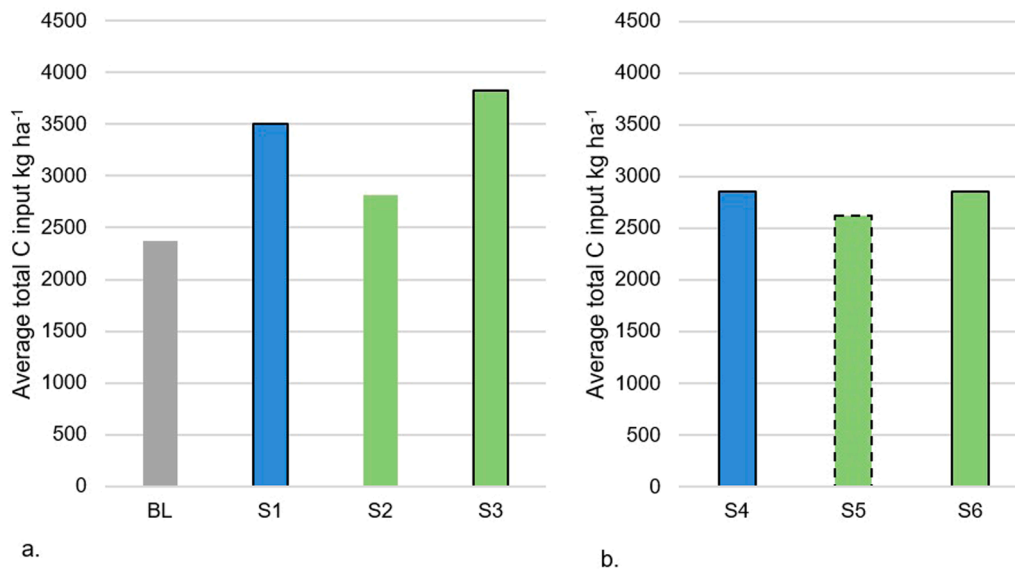


Fig. 2. System boundaries applied in the LCA. Fallow was included only in scenarios S1, S2, S3, which were assessed using the whole-farm area system boundary.



**Fig. 3.** Average total carbon (C) inputs ( $\text{kg ha}^{-1}$ ) into the soil in different scenarios. Blue bars indicate a 45% grain proportion and green bars a 30% grain proportion in the diet of dairy cows, while the baseline (BL) is shown in grey. The bar outlined with a dashed line represents the 10% yield increase scenario (S5), whereas bars outlined with a solid line represent scenarios with a 20% yield increase (S1, S3, S4, S6). Bars without an outline (BL and S2) represent scenarios with no assumed yield increase. Panel (a) shows scenarios in which the production area corresponds to the total farm area, while panel (b) shows scenarios in which calculations were applied to the forage production area only, reflecting the reduced production area.

### 3.3. Total life cycle GHG emissions

The total life cycle GHG emissions, combining whole-farm total climate impacts with emissions from land use (changes in SOC stocks), ranged from 2 272  $\text{Mg CO}_2\text{-eq yr}^{-1}$  (S6) to 3 682  $\text{Mg CO}_2\text{-eq yr}^{-1}$  (BL). Scenarios S1–S3 showed lower emissions compared to the baseline, and methane from enteric fermentation was the largest contributor across all scenarios (Fig. 7).

Assessment without SOC stock change varied from 2 298  $\text{Mg CO}_2\text{-eq yr}^{-1}$  (S6) to 2 580  $\text{Mg CO}_2\text{-eq yr}^{-1}$  (BL). The scenarios with improved crop yields (S1, S3, S4, S6) performed best with and without SOC stock change, although inclusion of SOC emphasized the difference. Within the SI scenarios excluding fallow from the system boundary (S4, S5, S6), total farm-level GHG emissions differed by only 1–2%. The mitigation impact resulted mainly from differences in enteric fermentation methane emission, manure management and feed crop cultivation emissions. S4 resulted with highest emissions from both enteric fermentation and feed crop cultivation, while its manure management emissions were lower in comparison to S5 and S6. Between S5 and S6, the difference resulted mainly from feed crop cultivation, S6 having the lowest emissions. Smaller difference was caused by the demand for purchased fertilisers and inputs, which was highest for S5 and lowest for S4. When SOC stock change was included in the assessment, S6 resulted in net carbon sequestration.

When fallow was included in the system boundary (S1, S2, S3), the ranking of scenarios remained the same with and without SOC stock change, but larger differences between scenarios were observed when SOC stock change was included compared to BL. Scenario S3 had the lowest total climate impact, 2 448  $\text{Mg CO}_2\text{-eq yr}^{-1}$  without SOC stock change and 3 383  $\text{Mg CO}_2\text{-eq yr}^{-1}$  with SOC stock change. Compared to BL, all scenarios showed improved performance, with mitigation impacts of 4–8% when SOC stock change was included and 2–5% without SOC stock change. As in the scenarios without fallow, the main differences resulted from enteric fermentation and manure management emissions. All scenarios performed better than BL regarding feed crop production. Enteric fermentation emissions were lower for S2 and S3, while S1 performed similarly to BL. This difference was offset by increased manure management emissions in S2 and S3, while S1 performed similarly to BL. Including SOC stock changes increased total

farm-level emissions by more than 40% compared to assessments excluding SOC. Nevertheless, the largest contribution to total climate impact was still from enteric fermentation (44–72%), followed by the SOC changes (0–30%) (Fig. 7).

When the total climate impact was allocated to milk production (per t of FPCM), productivity differences affected the results. In contrast to the whole-farm assessment, the product-level functional unit showed higher emissions in scenarios S2 and S3 (excluding SOC stock changes), and in S2 when SOC stock changes were included, compared to the baseline (Fig. 8). Scenarios BL, S1, and S4 showed the lowest climate impact per kg FPCM. These scenarios shared a 45% concentrate diet and higher productivity compared to scenarios with the same system boundaries.

The ranking of scenarios remained unchanged with and without SOC stock changes for scenarios without fallow (S4–S6) but changed slightly for scenarios including fallow (S1–S3), as BL and S3 switched order. This shift was caused by slightly higher SOC emissions in BL compared to S3. Among the fallow-including scenarios, S1 showed the lowest climate impact per kg FPCM, both with and without SOC. Scenarios with lower productivity and a 30% concentrate diet showed similar or higher climate impacts compared to BL. Specifically, S1 showed a 3% lower climate impact than BL without SOC stock change, and a 5% lower impact when SOC stock change was included. When SOC stock change was included, the mitigation contribution from farm processes was reduced to 2%, while SOC changes accounted for 3% of the total difference. The largest contributors were methane emissions from enteric fermentation and emissions from feed crop cultivation, both decreasing at similar rates.

The scenarios without fallow (S4–S6) showed similar productivity-related trends, with S4, combining a 45% concentrate diet and increased crop yields, showing the lowest climate impact per kg FPCM. As SOC stock changes contributed a sequestration effect in these scenarios, the ranking of scenarios remained nearly unchanged regardless of whether SOC emissions were included. The difference in climate impact between S4 and S5 was 8% with SOC stock change and 7% without SOC stock change, while the difference between S4 and S6 was 5% in both cases.

In addition to farm- and product-level assessments, environmental performance was evaluated using an area-based functional unit (per

**Table 2**

On-farm production areas, distribution of production to mineral and organic soils, harvested yield and soil C inputs from cropping in different scenarios.

Scenario		Area, ha			Harvested yield	C inputs kg ha <sup>-1</sup>		
		Total	Mineral soil	Organic soil		Crop residues	Roots	Root excreta
BL	Silage	125	100	25	3150	600	1816	1181
	Oat	50	40	10	1530	1796	594	244
	Barley	50	40	10	1530	1357	515	211
	Fodder area, ha	225						
	Total production area, ha	225						
S1	Released total area, ha							
	Silage	104	83.3	20.8	3780	720	2179	1417
	Oat	42	33.3	8.3	1836	2155	713	292
	Barley	42	33.3	8.3	1836	1628	619	254
	Green fallow	37	30	7.5	3150	600	1816	1181
S2	Fodder area, ha	188						
	Total production area, ha	225						
	Released total area, ha	37						
	Silage	144	115.2	28.8	3150	600	1816	1181
	Oat	29.25	23.4	5.9	1530	1796	594	244
S3	Barley	29.25	23.4	5.9	1530	1357	515	211
	Green fallow	22.50	18	4.5				
	Fodder area, ha	202.5						
	Total production area, ha	225						
	Released total area, ha	22.5						
S4	Silage	120	96	24	3780	720	2179	1417
	Oat	24	19.5	4.9	1836	2155	713	292
	Barley	24	19.5	4.9	1836	1628	619	254
	Green fallow	56.25	45	11.2				
	Fodder area, ha	169						
S5	Total production area, ha	225						
	Released total area, ha	56						
	Silage	104	97	7	3780	720	2179	1417
	Oat	42	42	0	1836	2155	713	292
	Barley	42	42	0	1836	1628	619	254
S6	Green fallow	0						
	Fodder area, ha	188						
	Total production area, ha	188						
	Silage	131	127	4	3465	660	1998	1299
	Oat	27	27	0	1683	1976	653	268
S7	Barley	27	27	0	1683	1492	567	232
	Green fallow	0						
	Fodder area, ha	184						
	Total production area, ha	184						
	Silage	120	120	0	3780	720	2179	1417
S8	Oat	24	24	0	1836	2155	713	292
	Barley	24	24	0	1836	1628	619	254
	Green fallow	0						
	Fodder area, ha	169						
	Total production area, ha	169						

hectare). Scenario rankings were similar to those observed in the whole-farm analysis. Scenario S3 showed the lowest impact per hectare, followed by S1, while BL showed the highest impact. Compared to BL, scenarios S1-S3 resulted in 2–5% lower climate impacts without SOC stock change and 4–8% lower impacts when SOC stock change was included.

Among the scenarios without fallow, S4 showed the lowest climate impact per hectare. Compared to S4, S5 showed a 2% higher impact without SOC stock change and 3% higher impact with SOC stock change, while S6 showed a 10% higher impact without SOC stock change and 11% higher impact with SOC stock change. Comparisons of scenarios are shown in Fig. 9 for assessment per cultivation area (ha).

#### 4. Discussion

Our study shows clear co-benefits between sustainable intensification and climate mitigation in boreal crop-livestock farming systems. Here, climate mitigation refers to management-driven reductions in GHG emissions and increases in SOC stocks under constant climatic conditions. Both yield improvements and reductions in the grain share of dairy cow diets increased soil carbon (C) inputs and soil organic carbon (SOC) stocks, while reducing overall greenhouse gas (GHG)

emissions. The findings demonstrate that targeted SI practices can simultaneously enhance productivity and environmental performance when implemented at the whole-farm level.

##### 4.1. Soil carbon dynamics

The scenarios of different SI options showed increased soil C inputs, resulting in corresponding increases in SOC stocks. The scenarios involving yield increases (S1, S3, S4, S5, S6) demonstrated a positive effect on soil carbon dynamics, reflecting the benefits of increased above- and below-ground biomasses and the possibility to feed the soil with green manure on land area no longer needed for fodder production. The estimated C input values per hectare varied significantly depending on whether the calculations were based on the total farm area (225 ha) or the fodder production area (169–188 ha). For example, scenarios S1 and S3, which utilized the total farm area, showed 23% and 25% higher C inputs than S4 and S6, which used only fodder production areas. Notably, in scenarios S1 and S3, green fallow in the spared land area contributed to increased average C input into the soil (Fig. 3). These results emphasize the importance of methodological assumptions made, in this case the involvement of spared land area in the scenario calculations, and explain sometimes contradictory results of impact

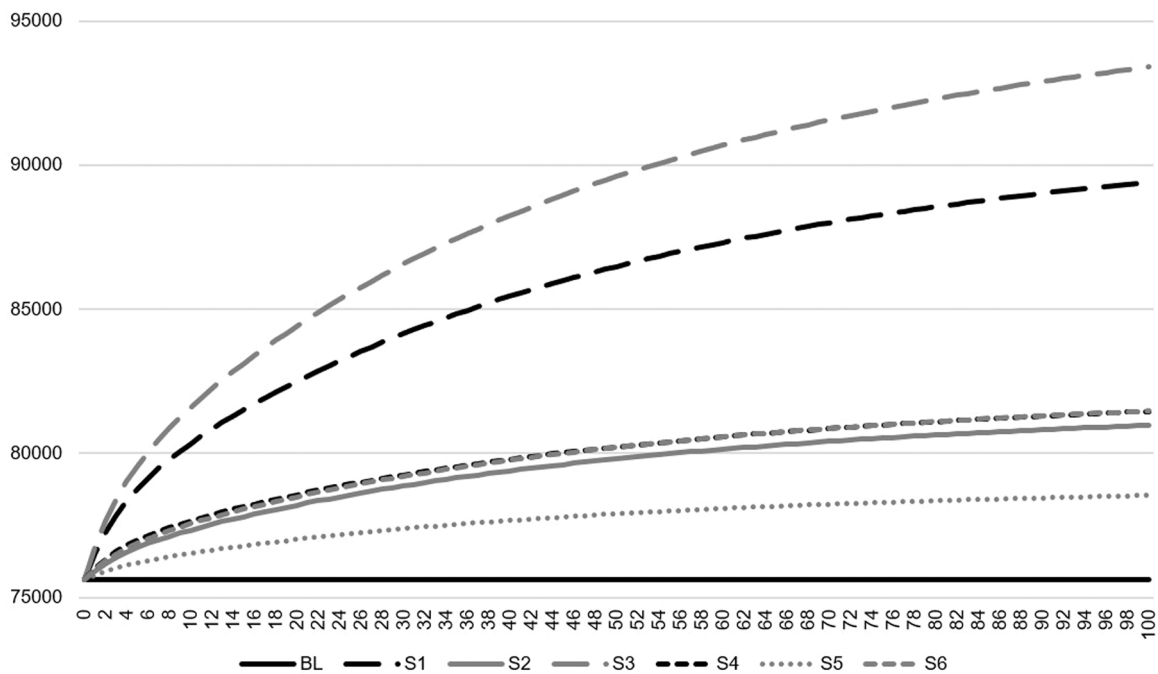


Fig. 4. Change in mineral soil organic carbon (SOC) stock ( $\text{kg C ha}^{-1}$ ) in different scenarios during 100-year simulation period. The change in SOC stock was calculated based on the difference between the baseline and different modelled scenarios.

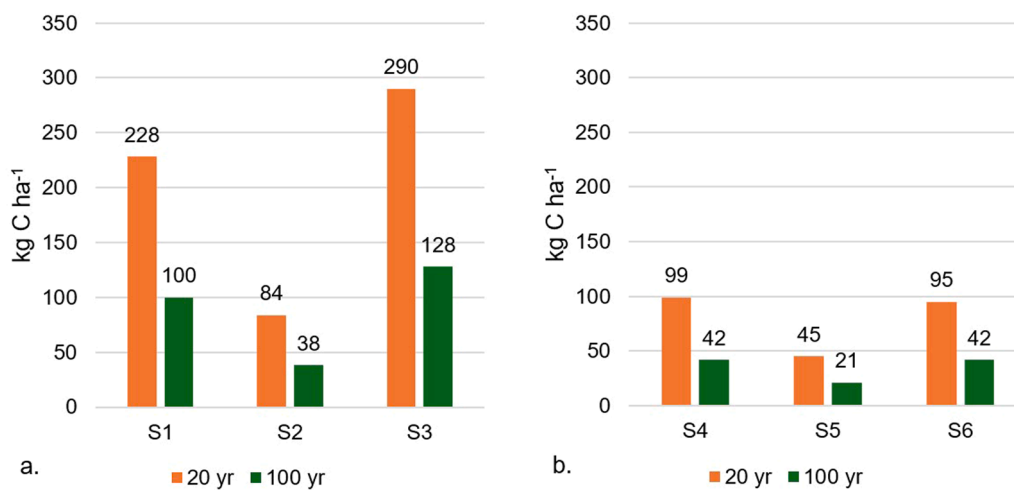


Fig. 5. Annual soil organic carbon (SOC) stock changes ( $\text{kg C ha}^{-1}\text{yr}^{-1}$ ) in different scenarios calculated for 20-year and 100-year simulation periods. Panels represent alternative system boundary assumptions: (a) total farm area and (b) forage production area only.

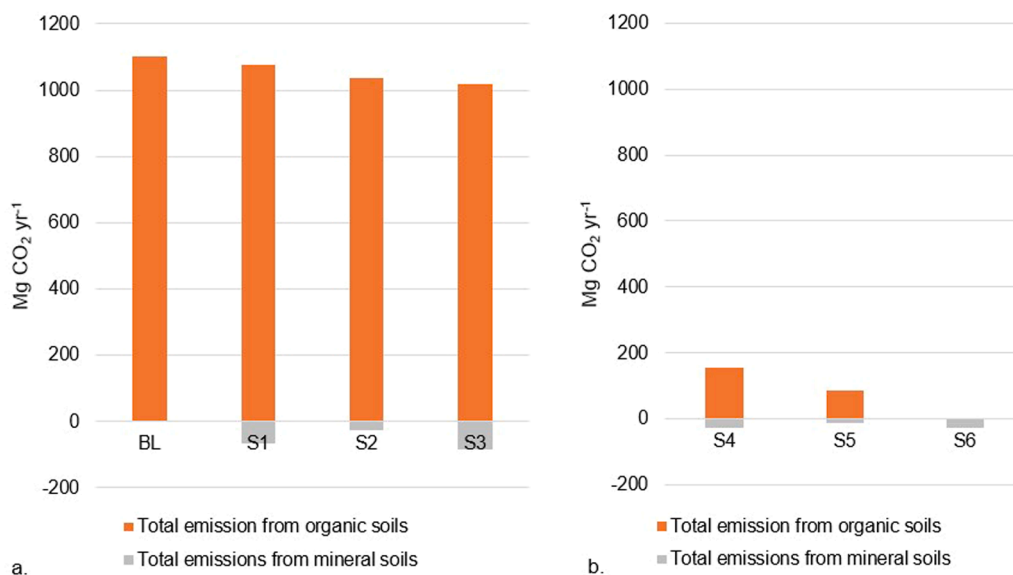
assessments (Joensuu et al., 2021).

The scenario involving a reduced grain proportion in dairy cow diets (S2) resulted in a 19% increase in average C inputs into the soil compared to the baseline. This substantial increase highlights the potential of dietary modifications to positively impact soil carbon dynamics by allocating more land for green crops, which could contribute additional organic matter to the soil. Higher soil C inputs of grasses in comparison to cereals have been reported in several studies (Kuzyakov and Domanski, 2000) although there are still considerable uncertainties in estimating, for example, the root biomass or the amount of rhizodeposition (Pausch and Kuzyakov, 2018).

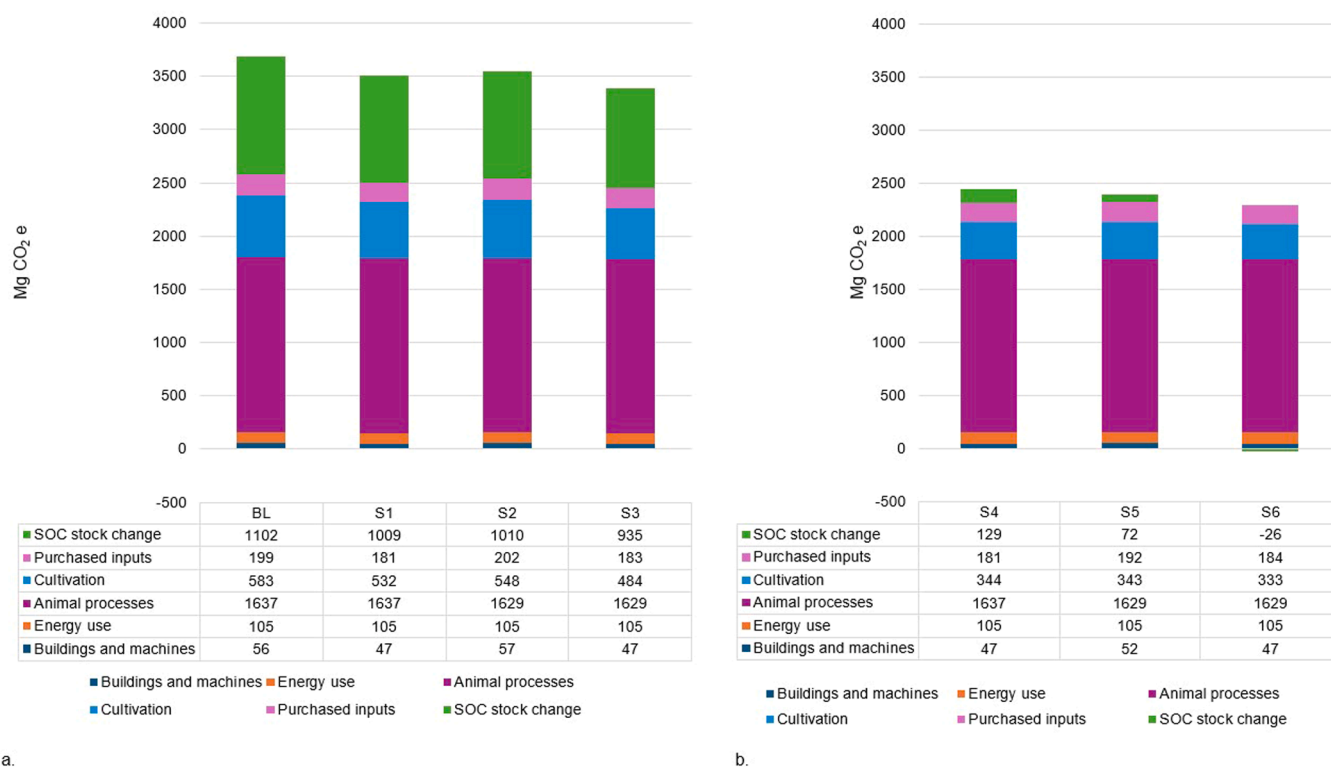
As a result of higher C inputs, the results of this study indicate an increase in SOC stock under SI scenarios over both 20-year and 100-year simulation periods. The difference in the results of different simulation periods reflects the sigmoid nature of C accumulation in the soil, which reaches its maximum rate within 5–10 years after implementing new

practices and then moderates until equilibrium is reached, typically after 15–100 years (Guo and Gifford, 2002). Consequently, a shorter simulation period tends to show more pronounced increases in SOC stocks. In this study, the 20-year simulation period yielded annual SOC stock change estimates that were 114–136% higher, depending on the scenario, compared to the 100-year simulation. This illustrates how the choice of time horizon strongly influences the magnitude of reported climate mitigation effects associated with the dynamic process of SOC sequestration (Joensuu et al., 2021).

The combination of yield increases, and a reduced grain diet (S3) resulted in the highest C inputs and SOC stock among all scenarios, highlighting the synergistic effects of combining multiple SI practices. This approach maximizes the carbon sequestration potential of boreal farming systems while improving both crop and livestock productivity. Additionally, diet modifications enhance soil carbon sequestration by allocating more land to green crops.



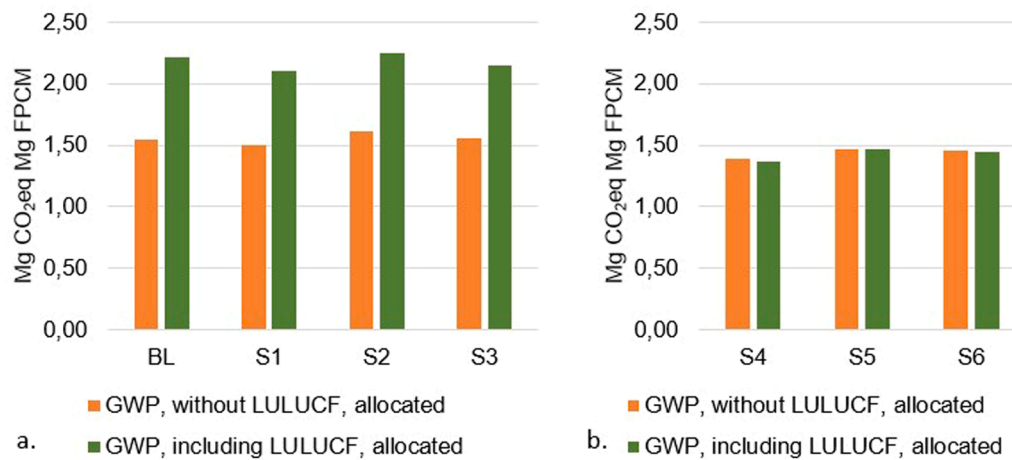
**Fig. 6.** Total soil-related emissions from mineral and organic soils (Mg CO<sub>2</sub>eq yr<sup>-1</sup>) across scenarios. Panels represent alternative system boundary assumptions: (a) total farm area and (b) forage production area only. In panel (b), released land area was assumed to be organic soil and was excluded from the calculation.



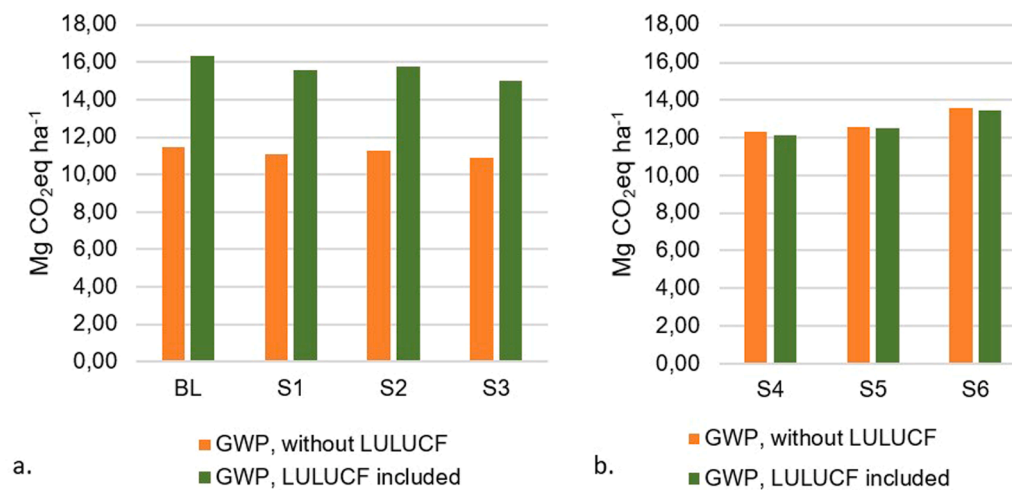
**Fig. 7.** Annual total life cycle greenhouse gas (GHG) emissions (Mg CO<sub>2</sub>eq yr<sup>-1</sup>) from the whole dairy farm, including LCA-based emissions and annualized soil organic carbon (SOC) stock changes. Panels (a) and (b) represent alternative system boundary assumptions: (a) total farm area and (b) forage production area.

The increase in productivity, leading to more efficient land use, demonstrated the potential to reduce land requirements and associated GHG emissions. The emission reductions are particularly high when land sparing is allocated to organic soils. In our results, production-related emission reductions were particularly high in scenarios S4, S5 and S6 that did not consider the emissions from the alternative land use. Cultivation of organic soils accelerates the decomposition of organic matter, leading to higher CO<sub>2</sub> emissions (Myhre et al., 2013) and reducing cultivation of these lands can significantly contribute to

climate change mitigation (Kekkonen et al., 2019). It is still important to notice that the emissions from alternative land uses of organic soils are very seldom completely emission-free. For example, organic soils that could be taken out of cultivation may be suitable for afforestation (Sarkkola, 2008). However, afforestation requires drainage, which can cause peat degradation if the peat remains above the water table. In such cases, rewetting is the most effective mitigation measure and has, in some instances, resulted in agricultural areas becoming carbon-neutral or even carbon sinks (Herbst et al., 2013). While these results are



**Fig. 8.** Total life cycle greenhouse gas (GHG) emissions per 1 000 kg fat and protein-corrected milk (FPCM) across scenarios, with and without soil organic carbon (SOC) stock changes. Panels (a) and (b) represent alternative system boundary assumptions: (a) total farm area and (b) forage production area only. Scenarios S1–S3 include fallow in the system boundary, whereas BL and scenarios S4–S6 exclude fallow.



**Fig. 9.** Total life cycle greenhouse gas (GHG) emissions per hectare of cultivated land across scenarios, with and without soil organic carbon (SOC) stock changes. Panels (a) and (b) represent alternative system boundary assumptions: (a) total farm area and (b) forage production area only. Scenarios S1–S3 include fallow in the system boundary, whereas BL and scenarios S4–S6 exclude fallow.

specific to Finnish boreal conditions with a high share of organic soils, similar mechanisms may be relevant for other northern crop–livestock systems with comparable soil and land-use characteristics.

#### 4.2. Life cycle GHG emissions at farm and product level

The LCA analysis was conducted with system boundaries including and excluding SOC stock change and with or without fallow. Assessments were made using multiple functional units representing whole-farm, product- and area-based perspectives. Using multiple functional units, with or without SOC stock change, scenarios with similar characteristics were highlighted as best performing. At the whole-farm level, improved yield, a high forage proportion and reduced cultivation of organic soils resulted in the lowest total climate impacts, as observed in scenarios S3 and S6. When the assessment was conducted per hectare, similarly, scenarios with improved yield and reduced organic soils, (S3 and S4) performed best compared to others within the same system boundaries. In product mass-based assessment per FPCM, deviations were observed due to the strong role of productivity, nevertheless, improved yields and reduced organic soils were also associated with better environmental performance (S1, S4). The results of the product

level assessment were consistent with previous studies on Finnish cattle production, which have similarly shown that productivity plays a major role when life cycle emissions are assessed at the product level (Huuskonen et al., 2023, 2025; Hietala et al., 2021).

The inclusion of SOC stock change affected scenario interpretations only slightly in terms of ranking. For scenarios with reduced organic soils and no fallow (S4–S6), the ranking order remained unchanged because SOC stock changes were small. However, for scenarios S1–S3, SOC stock change played a larger role, and when assessment per FPCM was applied, the ranking order changed. In this case, a higher forage proportion combined with improved crop yields (S3) was favoured over the BL scenario with higher milk productivity but average crop yield. This was due to smaller SOC change emission in comparison to BL. Overall, inclusion of SOC stock change affected the magnitude of total GHG emissions much more than the relative ranking of scenarios.

The inclusion of SOC stock change had a major impact on the magnitude of total GHG emissions and of the estimated mitigation potentials. Accounting for SOC altered the overall interpretation by highlighting the importance of soil-related processes, particularly emissions from organic soils, alongside animal-related sources. These findings underline that excluding SOC stock changes may lead to an incomplete

picture of climate mitigation potential in boreal dairy systems. Because scenarios including fallow (S1–S3) and those excluding fallow (S4–S6) apply different system boundaries, direct numerical comparisons between these groups should be interpreted with caution. This further emphasizes the importance of harmonised methods and the role of SOC stock change when included in LCA.

Independent of the functional unit applied, methane emissions from enteric fermentation remained the largest contributor to climate impacts in all scenarios, including the baseline, with or without SOC stock change. When SOC stock change was included, it became the second-largest contributor in scenarios including fallow, while its contribution remained low in scenarios without fallow. This reflects the magnitude of differences between assessments with and without SOC stock change. When SOC stock change was included, the contribution of other farm processes was either diluted (when SOC stock change increased emissions) or remained nearly unchanged (when SOC stock change was small or resulted in slight sequestration). From a mitigation perspective, inclusion of SOC stock change can therefore shift the identification of priority mitigation measures: Without SOC accounting, mitigation appears to focus on animal and cultivation processes, whereas inclusion of SOC highlights the importance of soil-related processes.

The time horizon used for SOC stock change followed Knudsen et al. (2019) and Petersen et al. (2013), applying a 100-year perspective. This approach reduces the relative emphasis on SOC stock change compared to other life cycle stages. It deviates from approaches such as the PEF method, which follows the PAS2050 approach and applies a 20-year time horizon (European Commission, 2021; BSI, 2011). While shorter time horizons may provide insights for practical decision-making, the 100-year time horizon ensures consistency with international climate assessment standards and provides a robust estimate of long-term mitigation potential. Based on these results, we recommend using a 100-year time horizon for integrating SOC stock changes into LCA, complemented by shorter-term results (e.g. 20 years) to inform near-term policy and management decisions. Given that annual SOC stock change estimates were 114–136% higher over a 20-year time span, shorter time horizons would particularly emphasize mitigation related to SOC dynamics, including both sequestration and emissions. This demonstrates how strongly time horizon selection influences the reported magnitude of mitigation potentials associated with SOC.

Previous studies have questioned whether mass-based functional units adequately capture the complexity of multifunctional production systems and have recommended parallel use of area-based functional units (Adewale et al., 2018; Hashemi et al., 2024; Pérez et al., 2024). In this study, scenarios were assessed using whole-farm and hectare-based functional units alongside mass-based assessment. Compared to product-based assessment, whole-farm assessment resulted in different performance rankings, particularly for scenarios without fallow. For scenarios including fallow, whole-farm and hectare-based assessments resulted in similar rankings, but these differed from product-based results. These findings are consistent with Hashemi et al. (2024), who observed lower impacts per hectare for organic farming while mass-based results were comparable, and with Pérez et al. (2024), who reported ranking differences depending on the selected functional unit. These findings underline the importance of using representative functional units, or multiple functional units in parallel, to capture both production efficiency and local environmental burdens. Pre-crop effects, green fallow and their impacts over multiple years remain important challenges for LCA. In this study, fallow was incorporated into the system boundary through system expansion, influencing production area, soil emissions and consequently climate impacts per kg FPCM.

Environmental and climate impact information is increasingly used by producers, industry, policy makers and consumers to guide mitigation efforts and support informed decision making. To provide reliable information, it is essential to apply methods with appropriate system boundaries, sensitive functional units and transparent identification of emission hot spots and mitigation potentials. In this study, SOC stock

change, including both carbon sequestration and emissions, was integrated into LCA and assessed using multiple functional units. Inclusion of SOC stock change had only a limited effect on scenario rankings, but a substantial effect on the magnitude of climate impacts and the contribution of different life cycle stages, particularly in systems with land use-related emissions. These results demonstrate the importance of including SOC stock change in LCA, while also highlighting the need for methodological consensus to ensure transparency and comparability across studies.

#### 4.3. Limitations and recommendations

The results of the study are based on computational assumptions and modelling approaches, which inherently include uncertainties. The simulated differences between scenarios are driven by the assumptions applied consistently across scenarios. While the results indicate that both yield increases and dietary modifications can significantly enhance soil carbon inputs and SOC stocks, the effectiveness of these practices in real-world conditions will depend on local factors, including soil type, climatic conditions, and existing management practices (Lessmann et al., 2022). Consequently, farmers and policy makers should adopt flexible strategies that allow SI practices and their combinations to be customized to local conditions, thereby maximizing their benefits.

Our findings highlight the potential of SI practices to contribute to management-driven climate mitigation in boreal regions. By increasing soil carbon inputs, these practices not only enhance SOC stocks but also improve soil health and resilience, supporting the long-term sustainability of agricultural systems (Cassman and Grassini, 2020). However, the range of SI-practices analysed in this study was relatively limited, potentially overlooking other management options that could influence carbon inputs, SOC stocks, and GHG emissions. The analysis focused on yield improvements and dietary modifications and did not include other potential mitigation measures such as manure processing technologies or novel feed additives.

The results are specific to boreal crop-livestock systems, particularly those with a high share of organic soils, which may limit their applicability to other climatic regions or agricultural systems. The use of the Yasso07 soil model and Carbon Calculator involves specific assumptions and parameters, which influence predicted SOC dynamics and emission estimates. While climate change impacts were not explicitly assessed here, it is important to note that rapid warming in the boreal region may affect crop yields (Palosuo et al., 2021) and SOC stocks (Heikkinen et al., 2022) and thereby affect the potential of SI options to mitigate emissions in a changing climate. This further highlights the urgency of various actions that would improve soil carbon stocks and agricultural production in the region. Furthermore, the current study did not fully capture interactions and synergies between multiple SI practices, which could significantly influence the overall effectiveness of SI strategies in reducing GHG emissions.

To realize the full climate benefits of SI practices, it is essential to implement them as part of integrated farm management strategies. Such strategies should address multiple challenges facing boreal agriculture, including climate variability, economic constraints, and the need for resilient production systems.

## 5. Conclusions

The study demonstrates that increasing yields through improved soil conditions and reducing grain proportions in dairy cow diets can significantly enhance management-driven climate mitigation, through reduced GHG emissions and increased SOC stocks, in boreal crop-livestock farming systems. Implementing these SI options together presents a promising strategy to improve the sustainability and climate resilience of agriculture in Finland and in comparable boreal regions with similar soil and land-use characteristics.

The findings highlight the critical role of organic soils as a major

source of GHG emissions in boreal farming systems. SI options that reduce the land area required for feed production can substantially lower emissions, especially when such reductions are targeted at organic soils. While completely banning the cultivation of organic soils is impractical in a peat-rich country like Finland, exploring mitigation strategies such as afforestation and rewetting remains essential. The effectiveness of these measures, however, depends strongly on site-specific conditions and management choices.

This study contributes to the existing literature by providing a whole-farm life cycle assessment that integrates SOC stock changes with productivity-enhancing and dietary SI strategies and evaluates outcomes using multiple functional units. Future research should focus on optimizing these practices, addressing potential trade-offs between productivity, emissions and land use, and considering the impacts of changing climate on production conditions and SOC stocks. In addition, integrating empirical field measurements (e.g. SOC and yield observations) with modelling would improve validation of key assumptions and strengthen the applicability of the results under boreal conditions. Additionally, socio-economic factors, such as costs, labour requirements and adoption barriers should be considered to assess the feasibility of SI options. Overall, integrating productivity-enhancing and emission-reducing management practices represents an important pathway toward low-emission dairy systems in boreal crop–livestock agriculture.

### CRedit authorship contribution statement

**Sanna Hietala:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Karoliina Rimhanen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Perttu Virkajärvi:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Auvo Sairanen:** Writing – review & editing, Validation, Methodology, Investigation, Data curation, Conceptualization. **Katri Joensuu:** Writing – review & editing, Methodology, Conceptualization. **Taru Palosuo:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

### 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.

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### Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.eja.2026.128105](https://doi.org/10.1016/j.eja.2026.128105).

### Data availability

Data will be made available on request.

### References

Adeawale, C., Reganold, J.P., Higgins, S., Evans, R.D., Carpenter-Boggs, L., 2018. Improving carbon footprinting of agricultural systems: boundaries, tiers, and organic farming. *Environ. Impact Assess. Rev.* 71, 41–48.

- Bessou, C., Tailleur, A., Godard, C., Gac, A., de la Cour, J.L., Boissy, J., Mischler, P., Caldeira-Pires, A., Benoist, A., 2020. Accounting for soil organic carbon role in land use contribution to climate change in agricultural LCA: which methods? Which impacts? *Int. J. Life Cycle Assess.* 25, 1217–1230. <https://doi.org/10.1007/s11367-019-01713-8>.
- Bianchi, A., Larmola, T., Kekkonen, H., Saarnio, S., Lång, K., 2021. Review of greenhouse gas emissions from rewetted agricultural soils. *Wetlands* 41, 108. <https://doi.org/10.1007/s13157-021-01507-5>.
- Bolinder, M.A., Kätterer, T., Andrén, O., Parent, L.E., 2012. Estimating carbon inputs to soil in forage-based crop rotations and modeling the effects on soil carbon dynamics in a Swedish long-term field experiment. *Can. J. Soil Sci.* 92, 821–833. <https://doi.org/10.4141/cjss2012-036>.
- BSI, 2011. PAS 2050:2011. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. British Standards Institution, London. (<https://knowledge.bsigroup.com/products/specification-for-the-assessment-of-the-life-cycle-greenhouse-gas-emissions-of-goods-and-services>).
- Cassman, K.G., Grassini, P., 2020. A global perspective on sustainable intensification research. *Nat. Sustain* 3, 262–268. <https://doi.org/10.1038/s41893-020-0507-8>.
- Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N., Leip, A., 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat. Food* 2, 198–209. <https://doi.org/10.1038/s43016-021-00225-9>.
- Davis, K.F., Gephart, J.A., Emery, K.A., Leach, A.M., Galloway, J.N., D'Odorico, P., 2016. Meeting future food demand with current agricultural resources. *Glob. Environ. Change* 39, 125–132. <https://doi.org/10.1016/j.gloenvcha.2016.05.004>.
- Del Prado, A., Mas, K., Pardo, G., Gallejones, P., 2013. Modelling the interactions between C and N farm balances and GHG emissions from confinement dairy farms in northern Spain. *Sci. Total Environ. Soil as a Source & Sink for Greenhouse Gases* 465, 156–165. <https://doi.org/10.1016/j.scitotenv.2013.03.064>.
- EDA (The European Dairy Association), 2018. Product Environmental Footprint Category Rules for Dairy Products.
- European Commission 2021. COMMISSION RECOMMENDATION of 16.12.2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations. Annex I. Product Environmental Footprint Method.
- EUROSTAT, 2025. Data – Eurostat. European Commission. Available at: (<https://ec.europa.eu/eurostat/data>). Accessed: 24 October 2025.
- FAO, 2018. Dairy and dairy products. OECD-FAO Agric. Outlook 2018–2027 2018.
- Folke, C., Hahn, T., Olsson, P., Norberg, J., 2005. Adaptive governance of social-ecological systems. *Annu. Rev. Environ. Resour.* 30, 441–473. <https://doi.org/10.1146/annurev.energy.30.050504.144511>.
- Goglio, P., Smith, W.N., Grant, B.B., Desjardins, R.L., McConkey, B.G., Campbell, C.A., Nemecek, T., 2015. Accounting for soil carbon changes in agricultural life cycle assessment (LCA): a review. *J. Clean. Prod.* 104, 23–39. <https://doi.org/10.1016/j.jclepro.2015.05.040>.
- Government of Finland, 2019. Inclusive and competent Finland: a socially, economically and ecologically sustainable society. Programme of Prime Minister Antti Rinne's Government.
- Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. *Glob. Change Biol.* 2002, 345–360. <https://doi.org/10.1046/j.1354-1013.2002.00486.x>.
- Hashemi, F., Mogensen, L., van der Werf, H.M.G., Cederberg, C., Knudsen, M.T., 2024. Organic food has lower environmental impacts per area unit and similar climate impacts per mass unit compared to conventional. *Commun. Earth Environ.* 5, 250. <https://doi.org/10.1038/s43247-024-01415-6>.
- Heikkinen, J., Keskinen, R., Kostensalo, J., Nuutinen, V., 2022. Climate change induces carbon loss of arable mineral soils in boreal conditions. *Glob. Change Biol.* 28, 3960–3973. <https://doi.org/10.1111/gcb.16164>.
- Herbst, M., Friborg, T., Schelde, K., Jensen, R., Ringgaard, R., Vasquez, V., Thomsen, A. G., Soegaard, H., 2013. Climate and site management as driving factors for the atmospheric greenhouse gas exchange of a restored wetland. *Biogeosciences* 10, 39–52. <https://doi.org/10.5194/bg-10-39-2013>.
- Herzog, A., Winckler, C., Zollitsch, W., 2018. Pursuit of sustainability in dairy farming: a review of interdependent effects of animal welfare improvement and environmental impact mitigation. *Agric. Ecosyst. Environ.* 267, 174–187. <https://doi.org/10.1016/j.agee.2018.07.029>.
- Hietala, S., Heusala, H., Katajajuuri, J.-M., Järvenranta, K., Virkajärvi, P., Huuskonen, A., Nousiainen, J., 2021. Environmental life cycle assessment of Finnish beef – cradle-to-farm gate analysis of dairy and beef breed beef production. *Agric. Syst.* 194, 103250. <https://doi.org/10.1016/j.agsy.2021.103250>.
- Huhtamäki, T., 2023. Tuotosseurantakarjojen rehunkulutus 2022. Maidontuotannon tulosesminaari 2023.
- Huhtanen, P., Rinne, M., Mäntysaari, P., Nousiainen, J., 2011. Integration of the effects of animal and dietary factors on total dry matter intake of dairy cows fed silage-based diets. *Animal* 5 (5), 691–702. (<https://www.cambridge.org/core/journals/animal/article/abs/integration-of-the-effects-of-animal-and-dietary-factors-on-total-dry-matter-intake-of-dairy-cows-fed-silagebased-diet/s/9620CAC0EA64351796432F8D1DCF5AC4>).
- Huuskonen, A., Hietala, S., Hyvönen, J., Leinonen, I., Manni, K., 2023. Environmental impacts and animal performance of finishing bulls fed different silage-based total mixed rations. *Livest. Sci.* 268, 105166. <https://doi.org/10.1016/j.livsci.2023.105166>.
- Huuskonen, A., Hietala, S., Pesonen, M., Manni, K., 2025. Effects of replacing timothy silage by red clover silage on environmental impacts, growth performance and carcass traits of finishing beef bulls. *Livest. Sci.* 299, 105755. <https://doi.org/10.1016/j.livsci.2025.105755>.

- IDF 2015. A common carbon footprint approach for Dairy. The IDF guide to standard life cycle assessment methodology for the dairy sector. Brussels, Belgium.
- Iivonen, S., Niemeläinen, O., Kokkinen, M., Jauhainen, L., 2024. Yield variation and yield potential of organic arable crops in Finland derived from statistical data. *Agric. Food Sci.* 33 (3), 212–222. (<https://journal.fi/afs/article/view/146579>).
- IPCC 2006. IPCC Guidelines for National Greenhouse Gas Inventories: Volume 4 Agriculture, Forestry and Other Land Use, IGES, Japan.
- IPCC 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK & New York, USA.
- Jensen, L.S., Salo, T., Palmason, F., Breland, T.A., Henriksen, T.M., Stenberg, B., Pedersen, A., Lundström, C., Esala, M., 2005. Influence of biochemical quality on C and N mineralisation from a broad variety of plant materials in soil. *Plant Soil* 273, 307–326. <https://doi.org/10.1007/s11104-004-8128-y>.
- Joensuu, K., Rimhanen, K., Heusala, H., Saarinen, M., Usva, K., Leinonen, I., Palosuo, T., 2021. Challenges in using soil carbon modelling in LCA of agricultural products—the devil is in the detail. *Int. J. Life Cycle Assess.* 26, 1764–1778. <https://doi.org/10.1007/s11367-021-01967-1>.
- Karhu, K., Gärdenäs, A.I., Heikkinen, J., Vanhala, P., Tuomi, M., Liski, J., 2012. Impacts of organic amendments on carbon stocks of an agricultural soil — comparison of model-simulations to measurements. *Geoderma* 189–190, 606–616. <https://doi.org/10.1016/j.geoderma.2012.06.007>.
- Kekkonen, H., Ojanen, H., Haakana, M., Latukka, A., Regina, K., 2019. Mapping of cultivated organic soils for targeting greenhouse gas mitigation. *Carbon Manag.* 10, 115–126. <https://doi.org/10.1080/17583004.2018.1557990>.
- Knudsen, M.T., Dorca-Preda, T., Djomo, S.N., Peña, N., Padel, S., Smith, L.G., Zollitsch, W., Hörtenhuber, S., Hermansen, J.E., 2019. The importance of including soil carbon changes, ecotoxicity and biodiversity impacts in environmental life cycle assessments of organic and conventional milk in Western Europe. *J. Clean. Prod.* 215, 433–443. <https://doi.org/10.1016/j.jclepro.2018.12.273>.
- Korhonen, I., 2024. Ruokinnan tunnusluvut vuodelta 2024. Pro Agria Itä-Suomi. In Finnish. ([https://www.proagria.fi/uploads/ProAgria/Tiedostot/Ruokinnan\\_tunnusluvut\\_vuodelta\\_2024.pdf](https://www.proagria.fi/uploads/ProAgria/Tiedostot/Ruokinnan_tunnusluvut_vuodelta_2024.pdf)). Accessed 14 January 2026.
- Kuoppala, K., Vattulainen, J., Perttilä, S., Saastamoinen, M., Rinne, M., 2024. Finnish Feed Tables and Nutrient Requirements: Ruminants, pigs, poultry, horses. *Natural Resources and Bioeconomy Studies 70/2024*. Natural Resources Institute Finland, Helsinki, p. 97.
- Kuzyakov, Y., Domanski, G., 2000. Carbon input by plants into the soil. *Rev. J. Plant Nutr. Soil Sci.* 163, 421–431. [https://doi.org/10.1002/1522-2624\(200008\)163:4%253C421::AID-JPLN421%253E3.0.CO;2-R](https://doi.org/10.1002/1522-2624(200008)163:4%253C421::AID-JPLN421%253E3.0.CO;2-R).
- Lehtilä, A., Ghani, H.U., Liu, X., Palosuo, T., Tuomisto, H.L., Leinonen, I., 2025. Framework for including national-level LULUC emissions and removals in the GWP of agricultural and forestry products in LCA. *J. Clean. Prod.* 494, 144999. <https://doi.org/10.1016/j.jclepro.2025.144999>.
- Lehtonen, H., Palosuo, T., Korhonen, P., Liu, X., 2018. Higher crop yield levels in the North Savo Region—means and challenges indicated by farmers and their close stakeholders. *Agriculture* 8, 93. <https://doi.org/10.3390/agriculture8070093>.
- Lessmann, M., Ros, G.H., Young, M.D., de Vries, W., 2022. Global variation in soil carbon sequestration potential through improved cropland management. *Glob. Change Biol.* 28, 1162–1177. <https://doi.org/10.1111/gcb.15954>.
- Lipper, L., Mann, W., Meybeck, A., Sessa, R., 2010. Climate-smart” agriculture: policies, practices and financing for food security, adaptation and mitigation. FAO.
- Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. *Nature* 490, 254–257. <https://doi.org/10.1038/nature11420>.
- Myhre, G., Shindell, D., Bréon, F.M., Collins, W., Fuglestedt, J., Huang, J., Koch, D., Lamarque, J.F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013. Anthropogenic and natural radiative forcing, in *Climate Change 2014: The Physical Science Basis*. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., et al. (Eds.), *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge; New York, NY, pp. 659–740.
- OSF, 2025. Official Statistics of Finland. Structure in Agriculture and horticulture. Natural Resources Institute Finland. Available at: (<https://stat.luke.fi/en>) Accessed 24 October 2025.
- Palosuo, T., Heikkinen, J., Regina, K., 2015. Method for estimating soil carbon stock changes in Finnish mineral cropland and grassland soils. *Carbon Manag.* 6, 207–220. <https://doi.org/10.1080/17583004.2015.1131383>.
- Palosuo, T., Hoffmann, M.P., Rötter, R.P., Lehtonen, H.S., 2021. Sustainable intensification of crop production under alternative future changes in climate and technology: the case of the North Savo region. *Agric. Syst.* 190, 103135. <https://doi.org/10.1016/j.agsy.2021.103135>.
- Pausch, J., Kuzyakov, Y., 2018. Carbon input by roots into the soil: quantification of rhizodeposition from root to ecosystem scale. *Glob. Change Biol.* 24, 1–12. <https://doi.org/10.1111/gcb.13850>.
- Pérez, R., Argüelles, F., Laca, A., Laca, A., 2024. Evidencing the importance of the functional unit in comparative life cycle assessment of organic berry crops. *Environ. Sci. Pollut. Res.* 31 (14), 22055–22072.
- Petersen, B.M., Knudsen, M.T., Hermansen, J.E., Halberg, N., 2013. An approach to include soil carbon changes in life cycle assessments. *J. Clean. Prod.* 52, 217–224. <https://doi.org/10.1016/j.jclepro.2013.03.007>.
- Pettygrove, G.S., Heinrich, A.L., Eagle, A.J., 2009. Dairy Manure Nutrient Content and Forms. University of California.
- Ramin, M., Huhtanen, P., 2013. Development of equations for predicting methane emissions from ruminants. *J. Dairy Sci.* 96, 2476–2493. <https://doi.org/10.3168/jds.2012-6095>.
- Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F., Dribe, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummer, 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. *Sci. Adv.* 9, eadh2458. <https://doi.org/10.1126/sciadv.adh2458>.
- Riggers, C., Poelau, C., Don, A., Bamminger, C., Höper, H., Dechow, R., 2019. Multi-model ensemble improved the prediction of trends in soil organic carbon stocks in German croplands. *Geoderma* 345, 17–30. <https://doi.org/10.1016/j.geoderma.2019.03.014>.
- Roe, S., Streck, C., Obersteiner, M., Frank, S., Griscom, B., Drouet, L., Fricko, O., Gusti, M., Harris, N., Hasegawa, T., Hausfather, Z., Havlik, P., House, J., Nabuurs, G.-J., Popp, A., Sánchez, M.J.S., Sanderman, J., Smith, P., Stehfest, E., Lawrence, D., 2019. Contribution of the land sector to a 1.5 °C world. *Nat. Clim. Change* 9, 817–828. <https://doi.org/10.1038/s41558-019-0591-9>.
- Sarkkolla, S., 2008. Greenhouse effect of the use of peat and peatlands in Finland. Final report. Helsinki: Publications of Ministry of Agriculture and Forestry.
- Statistics Finland, 2024. Greenhouse gas emissions in Finland 1990–2022. National Inventory Report under the UNFCCC and the Kyoto Protocol. Helsinki. ([https://unfccc.int/sites/default/files/resource/FI\\_NID\\_UN\\_2022\\_2024-12-16.pdf](https://unfccc.int/sites/default/files/resource/FI_NID_UN_2022_2024-12-16.pdf)).
- Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci.* 108, 20260–20264. <https://doi.org/10.1073/pnas.1116437108>.
- Tuomi, M., Rasinmäki, J., Repo, A., Vanhala, P., Liski, J., 2011. Soil carbon model Yasso07 graphical user interface. *Environ. Model. Softw.* 26, 1358–1362. <https://doi.org/10.1016/j.envsoft.2011.05.009>.
- Tuomisto, H.L., De Camillis, C., Leip, A., Nisini, L., Pelletier, N., Haastrup, P., 2015. Development and testing of a European Union-wide farm-level carbon calculator. *Integr. Environ. Assess. Manag.* 11, 404–416. <https://doi.org/10.1002/ieam.1629>.
- Tzemi, D., Lehtonen, H., 2022. The use of pre-crop values to improve farm performance: the case of dairy farms in southwest Finland. *Int. J. Agric. Sustain* 20, 1333–1347. <https://doi.org/10.1080/14735903.2022.2131042>.
- Virkkäjärvä, P., Rinne, M., Mononen, J., Niskanen, O., Järvenranta, K., Sairanen, A., 2015. Dairy production systems in Finland, in: *Grassland and Forages in High Output Dairy Farming Systems*, Vol 20. Proceedings of the 18th Symposium of the European Grassland Federation. Wageningen, the Netherlands.
- Wang, C., Amon, B., Schulz, K., Mehdi, B., 2021. Factors that influence nitrous oxide emissions from agricultural soils as well as their representation in simulation models: a review. *Agronomy* 11, 770. <https://doi.org/10.3390/agronomy11040770>.
- Westhoek, H., Lesschen, J.P., Rood, T., Wagner, S., De Marco, A., Murphy-Bokern, D., Leip, A., van Grinsven, H., Sutton, M.A., Oenema, O., 2014. Food choices, health and environment: effects of cutting Europe’s meat and dairy intake. *Glob. Environ. Change* 26, 196–205. <https://doi.org/10.1016/j.gloenvcha.2014.02.004>.